

**UNIVERSITY OF SCIENCE AND TECHNOLOGY**  
**FACULTY OF MECHANICAL ENGINEERING**



# **GRADUATION REPORT – CAPSTONE PROJECT**

**TOPIC:**

**DESIGN OF ASSEMBLY PROCESS AND  
EVALUATION OF GD&T INFLUENCE ON  
ACCURACY AND STRESS OF NOSE LANDING  
GEAR**

<b>Faculty:</b>	Mechanical Engineering
<b>Major:</b>	<b>AEROSPACE MECHANICS</b>
<b>Name:</b>	Vo Phuoc Linh
<b>Student ID:</b>	101200448
<b>Supervisor:</b>	Dr. Nguyen Ba Kien
<b>Class:</b>	20CKHK

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## PREFACE

In aerospace engineering, precision in the manufacturing and assembly of mechanical systems plays a decisive role in overall system reliability. A typical example is the nose landing gear (NLG), which integrates multiple functions including dynamic load bearing, shock absorption, and directional control. With a structure composed of multiple joints and pins, even minor assembly deviations can significantly affect local stress concentrations, kinematic stability, and service life.

This thesis focuses on the development of an assembly procedure and the evaluation of geometric deviations introduced during assembly. Finite Element Method (FEM) simulations are used to compare ideal and imperfect assembly cases to observe their impact on structural performance.

I would like to express my sincere gratitude to my academic advisor for the valuable guidance and support throughout this project. I also extend my appreciation to the faculty, friends, and family who have supported me during this academic journey.

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Student

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## Chapter 1 INTRODUCTION

### 1.1. Aerospace context:

#### 1.1.1. Aviation – A key driver of progress and a symbol of technological excellence:

Since the historic flight by the Wright brothers, the aerospace industry has evolved at an extraordinary pace. It has become one of the most powerful engines driving globalization and human advancement. Far beyond a means of transportation, aviation has built a global network—shrinking geographical barriers, facilitating commerce, enabling tourism, and supporting cross-cultural exchange. It plays a vital role in “just-in-time” supply chains, humanitarian relief operations, and national defense systems. A robust aviation sector is not just a logistical asset—it reflects a nation's technological capacity and standing on the global stage.

Every commercial aircraft today represents a pinnacle of multidisciplinary engineering. It integrates advanced aerodynamics, high-performance lightweight materials, efficient propulsion systems, and highly complex avionics. Yet, beneath this high-tech sophistication lies a core principle that governs every design and manufacturing decision: safety and reliability. Aviation operates under the strictest safety regulations in all of engineering, where allowable errors are pushed as close to zero as possible.



Figure 1.1. Global Supply Chain of a Commercial Aircraft (Source: Internet)

### ***1.1.2. Mechanical precision – the silent enabler behind every safe flight:***

This high level of safety is not incidental. It is the result of meticulous mechanical precision. A single aircraft comprises millions of parts, manufactured by suppliers around the world. For these components to fit together seamlessly during final assembly – and to perform reliably over decades of service – the demands on manufacturing and assembly precision are extremely high.

Even a minor deviation, on the order of a few microns, might not cause immediate failure. However, as these tolerances accumulate across multiple stages of assembly (known as tolerance stack – up), they can result in serious consequences:

- Increased friction or jamming in moving parts, leading to accelerated wear or premature failure.
- Localized stress concentrations that may initiate fatigue cracks.
- Reduced system performance, such as hydraulic leakage or abnormal vibration.

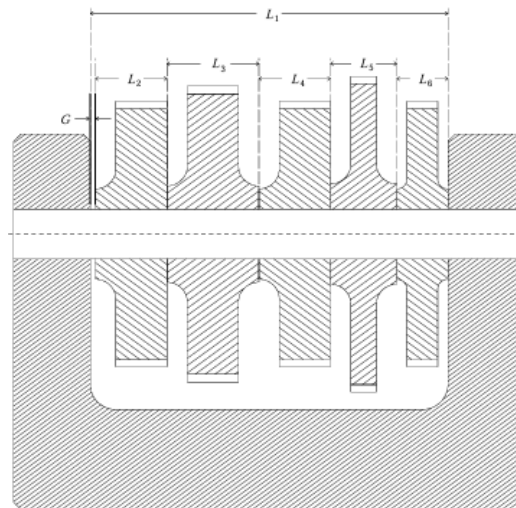


Figure 1.2. Tolerance Stack Example (Fritz Scholz, *Tolerance Stack Analysis Methods*, 1995)

As a result, it is essential to control not only dimensions, but also geometric attributes such as form, orientation, and the relative positions between surfaces and axes. This is precisely where Geometric Dimensioning and Tolerancing (GD&T) plays a critical role. GD&T provides the framework to specify, communicate, and verify these geometric requirements – making it indispensable in modern aerospace manufacturing.

This study will examine the influence of GD&T through the lens of one of the most complex and safety-critical assemblies in an aircraft: the Nose Landing Gear (NLG).

## **1.2. The position and role of the nose landing gear (NLG):**

### ***1.2.1. The landing gear system – a foundation for critical flight phases:***

On any aircraft, the landing gear system is one of the most complex, heavy, and expensive mechanical systems. It serves as the interface between the aircraft and the ground, bearing the most intense operational phases: takeoff and landing. A typical configuration includes two main landing gear assemblies (Main Landing Gear – MLG) located near the aircraft's center of gravity, and a nose landing gear (Nose Landing Gear – NLG) positioned at the front. While the main gear supports approximately 90% of the static and dynamic load, the NLG fulfills highly specialized functions critical to ground handling and directional control.

### ***1.2.2. Multi – functional capabilities of the nose landing gear (NLG):***

The nose gear is far more than a simple structural support. It integrates multiple subsystems, each demanding high precision and reliability.

- **Load bearing and shock absorption**

The most fundamental role of the NLG is to support the forward section of the aircraft and absorb dynamic loads. Although it does not bear as much landing force as the main gear, it still endures significant impact. More importantly, during taxiing over uneven surfaces, the NLG experiences continuous shock inputs. Central to this function is the oleo-pneumatic strut—a complex cylinder combining compressed gas (as a spring) and hydraulic fluid (as a damping medium). It dissipates energy efficiently through throttling orifices. The smooth operation of this piston system relies entirely on the concentricity and surface finish of the working components.

- **Steering and ground control:**

What truly sets the NLG apart is its steering capability. It allows pilots to maneuver the aircraft on the ground using a hydraulically driven swivel mechanism controlled by the cockpit tiller and rudder pedals. High precision in the steering system is essential, from low-speed movements in tight spaces to maintaining directional stability during high-

speed takeoff rolls. Any backlash or deviation in the steering joints or pin connections can lead to degraded control and pose safety risks.

- **Retraction, extension, and locking mechanism:**

To reduce aerodynamic drag, the NLG must fully retract into its housing during flight. This action involves a tightly sequenced operation: opening gear doors, unlocking the downlocks, retracting the strut with hydraulic actuators, securing the uplocks, and finally closing the doors. Each step must proceed smoothly within a specified timeframe. Position sensors (up-lock and down-lock) must accurately confirm locked status. Assembly misalignments can cause interference during retraction or, worse, result in incomplete locking—an immediate flight safety concern.

- **Shimmy damping**

A known and potentially dangerous phenomenon in nose gears is shimmy—a self-excited oscillation that causes rapid lateral vibration of the wheel assembly. Shimmy can damage tires, compromise structural components, and impair steering control. To counter this, a shimmy damper is integrated into the system. Its performance heavily depends on the stiffness of the entire assembly and the elimination of unnecessary clearances in pin joints and pivot points.

Due to the complexity and critical nature of these functions, the NLG is an ideal subject for investigating the impact of manufacturing and assembly deviations. Even minor misalignments—such as a small angular error in the parallelism of pin holes—can redistribute stresses, accelerate wear, reduce steering precision, and contribute to shimmy onset. Quantifying these effects through simulation is the central focus of this study.

### **1.3. The importance of GD&T in the aerospace industry:**

In a globalized manufacturing environment where aircraft components may be produced in different countries and assembled elsewhere, relying solely on traditional plus/minus dimensional tolerancing is no longer sufficient. To meet the extreme precision and consistency required in aerospace engineering, Geometric Dimensioning and Tolerancing (GD&T) has become the standardized technical language used to define part geometry, assembly intent, and inspection criteria.

Unlike basic tolerancing, GD&T does more than specify “how big” a feature should be. It also defines how that feature should be shaped, and where it should be located relative to datums, surfaces, or centerlines. In aerospace, where functional safety and interchangeability are non-negotiable, GD&T plays a foundational role in ensuring product quality.

Key benefits of GD&T in aerospace include:

- **Ensuring interchangeability**

Components manufactured in one country—such as the United States—must fit perfectly into assemblies being built or maintained elsewhere, such as Vietnam. GD&T enables this by precisely controlling geometric features such as flatness, concentricity, perpendicularity, parallelism, and hole location. This allows parts from different sources to function together seamlessly.

- **Optimizing functionality and durability**

per application of GD&T ensures that moving assemblies, such as the retraction or extension mechanisms in landing gear, operate smoothly without binding, misalignment, or uneven wear. By preventing stress concentrations and unintended interference fits, GD&T directly contributes to longer service life and increased system reliability.

- **Bridging design and manufacturing**

GD&T provides a clear, unambiguous communication channel between design, manufacturing, and quality control teams. It helps reduce interpretation errors, minimize rework, and cut down on unnecessary production costs by making design intent explicit and measurable.

#### **1.4. Simulation and tolerance analysis using modern engineering software:**

Historically, the evaluation of tolerance effects relied heavily on theoretical calculations and costly physical prototyping. Today, advances in computational engineering have enabled the use of Finite Element Analysis (FEA) as a powerful virtual laboratory. Engineers can now simulate how geometric deviations affect real-world performance before committing to fabrication, reducing both cost and development time.

With modern tools, the simulation process includes the following steps:

- Creating accurate 3D models of individual parts and complete assemblies, including mechanical interfaces such as pin–hole fits.
- Applying realistic boundary conditions and loads, such as landing impact forces or internal hydraulic pressure, to replicate operational environments.
- Introducing intentional geometric deviations, such as hole misalignment or surface flatness errors, within the allowed GD&T tolerances, to assess their influence on performance.
- Analyzing stress distributions, deformation, contact pressure, and sliding behavior, which helps predict potential failure modes such as fatigue cracking, accelerated wear, or mechanical binding.

Design platforms like CATIA and Siemens NX are widely used to define tolerances using GD&T, supporting both the geometric modeling and annotation processes. On the simulation side, software like Abaqus, ANSYS, and MSC Nastran are essential for advanced structural analysis. Among these, Abaqus is selected for this project due to its strong capabilities in handling nonlinear contact problems, which are particularly important when simulating interactions between mating surfaces such as pins and holes.

In this study, contact analysis is the core method used to investigate how even minor deviations in parallelism or concentricity can affect stress concentration, load transfer, and alignment accuracy in the nose landing gear assembly. By leveraging simulation, engineers gain deep insights that would be difficult or impractical to obtain through traditional testing alone.

### **1.5. Objectives of the study:**

This thesis, titled “*Design of Assembly Process and Evaluation of GD&T Influence on Accuracy and Stress of the Nose Landing Gear*”, aims to achieve the following specific objectives:

- **Develop and standardize an assembly process**

The study will examine and systematize the assembly procedure for a representative subassembly of the nose landing gear – such as the torque link pin joint – based on technical documentation and manufacturer specifications. The focus will be on

identifying key assembly steps that critically affect positional accuracy and functional performance of the overall system.

- **Simulate and analyze the impact of geometric deviations**

Using Abaqus finite element analysis (FEA) software, the project will create a detailed simulation model of the pin-hole assembly. The study will systematically investigate how specific GD&T deviations – particularly parallelism errors between hole centerlines – affect stress distribution and deformation when subjected to loading conditions that simulate in – service operation.

- **Evaluate the role of GD&T in structural performance**

From simulation results, the research will assess the significance of implementing and maintaining geometric tolerances. It will clarify the correlation between GD&T control and structural integrity, assembly precision, and long-term operational reliability of the nose landing gear.

- **Propose practical recommendations**

Based on quantitative findings, the study will formulate actionable recommendations regarding the control of geometric tolerances during manufacturing and quality inspection (e.g., CMM, optical scanning). These guidelines aim to optimize mechanical performance and extend the service life of critical subcomponents, contributing to safer and more efficient aerospace design practices.

## Chapter 2

### **THEORETICAL BACKGROUND**

#### **2.1. Overview of the nose landing gear system:**

##### ***2.1.1. Structural function and shock absorption mechanism of the NLG:***

Within an aircraft's landing gear system, the Nose Landing Gear (NLG) supports the forward fuselage and maintains directional stability during taxiing, takeoff, and landing. Although it carries less vertical load than the main landing gear, the NLG endures significant transient forces upon ground contact – especially when operating on uneven surfaces or during sudden braking and steering maneuvers.

##### **Oleo-pneumatic Shock Absorber – The Core of Impact Damping**

At the heart of the NLG is a sophisticated oleo-pneumatic strut, a cylinder system that combines compressed gas and hydraulic oil to absorb and dissipate impact energy.

Its internal structure consists of two main chambers:

- A gas chamber (typically nitrogen) acts as a spring. When compressed, it stores energy and provides restorative force.
- A hydraulic oil chamber provides damping. As the piston moves under load, oil is forced through calibrated orifices, generating resistance that slows down the motion and dissipates energy as heat.

This dual – action mechanism ensures that both shock absorption and controlled motion occur simultaneously during landing or ground vibrations. The result is a smoother transfer of load and reduced stress on the airframe.

The effectiveness of this system depends on several factors:

- Pre-charged gas pressure, which determines the strut's spring stiffness;
- Size and shape of the throttling orifices, which govern the damping response;
- Concentricity and surface finish of sliding parts, which affect friction, sealing quality, and long-term reliability.

##### **Operational Stability and Reliability**

- Since the NLG functions based on hydraulic-pneumatic principles, even small geometric or assembly deviations – such as misalignment between the piston and cylinder axis or out-of-spec surface roughness – can impair system performance. Issues like piston sticking, oil leakage, or damping loss may arise.
- This highlights the necessity of tight tolerance control during manufacturing and assembly. The insights provided here lay the theoretical groundwork for simulation-based evaluations of how geometric deviations influence the NLG’s mechanical behavior.

### ***2.1.2. General structure of the nose landing gear:***

The nose landing gear is a complex assembly comprising multiple mechanical components that work together to enable extension, retraction, shock absorption, and ground steering. The primary elements include the drag strut, lockstay, nose gear actuator, shock strut, and – on certain aircraft such as the Airbus A320 – a dedicated shock absorber.

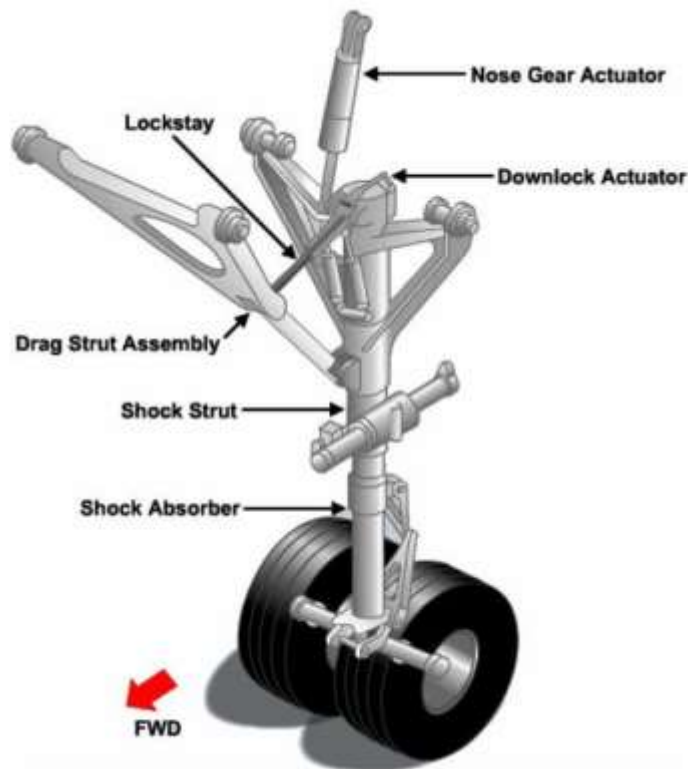


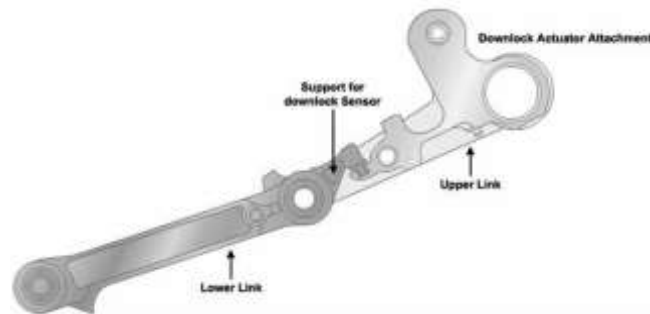
Figure 2.1. General structure of the NLG

- **Drag strut**

The drag strut stabilizes the shock strut in the longitudinal (fore – aft) direction and locks the nose gear in both the extended and retracted positions. It is sometimes referred to as the drag stay or drag brace. The drag strut assembly includes a forestay and a tubular arm connected via a universal joint. This assembly provides the primary structural support when the gear is in the down-and-locked configuration and includes an uplock roller for securing the gear in the retracted position. On the Airbus A320, the forestay is typically made from aluminum and is attached to the aircraft structure via two trunnions.

- **Lockstay**

The lockstay acts as a secondary locking mechanism during gear extension. It ensures proper alignment of the folding drag strut and consists of two links connected through a spherical bearing. The upper link – made from forged aluminum – is hinged to the top of the shock strut outer cylinder and also interfaces with the downlock actuator. It houses two sensor mounts that detect the down-and-locked status. The lower link is constructed from steel and connects to the forestay of the drag strut.

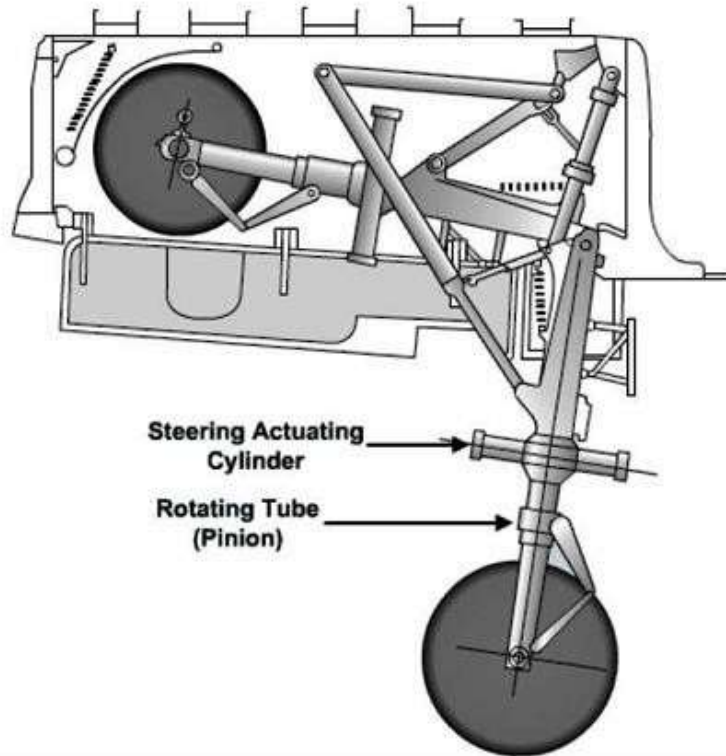


- **Actuator**

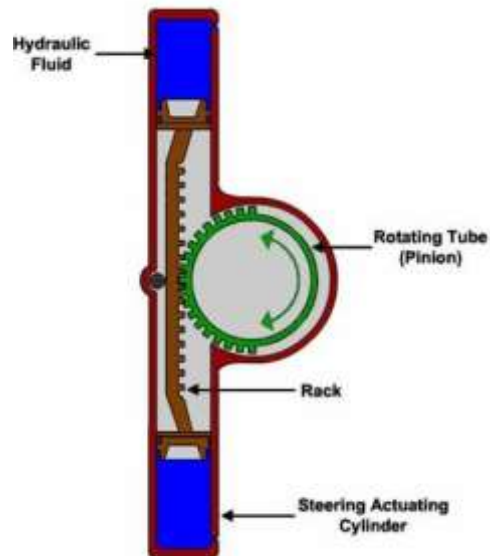
The nose gear actuator converts hydraulic pressure into mechanical force to extend or retract the landing gear. The actuator housing is mounted to the airframe, while the actuator rod is linked to the shock strut via a mounting lug.

- **Nose gear shock strut**

The shock strut is inclined slightly forward and aligns with the wheel axle. In this configuration, the nose wheels are free to return to the centerline. Two trunnions serve as hinge points and contain spherical bearings – two connecting to the drag stay and two to the strut body.



Inside the strut, a rotating tube engages with a rack. A hydraulic steering actuator, mounted parallel to the aircraft centerline, drives the rack – and – pinion mechanism to rotate the nose wheels. This layout minimizes the risk of tire tread separation.



- **Shock absorber**

In nose landing gear assemblies, the shock absorption system plays a critical role in damping impact loads during landing and ground operations. While most aircraft use a two – tube configuration consisting of an outer cylinder and an inner sliding piston, certain designs – such as the Airbus A320 – incorporate a more complex four – tube structure for improved energy dissipation and steering integration.

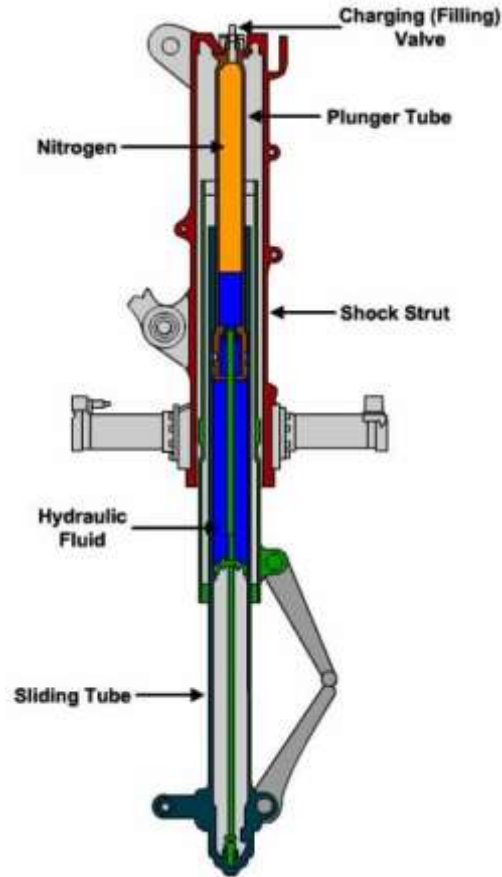
The shock strut in the A320 comprises the following components:

- Outer cylinder (shock strut body): Provides the primary structural enclosure and houses the remaining internal components.
- Sliding tube: Moves vertically within the outer cylinder to allow compression during impact.
- Plunger tube: Internally nested within the sliding tube, it forms the upper moving part of the shock absorbing mechanism.
- Rotating tube: Located inside the plunger, it integrates with the nose wheel steering system through a rack-and-pinion connection.

The shock absorber assembly itself is formed by the interaction between the sliding tube and the plunger tube. The space between these tubes is filled with a mixture of hydraulic fluid and compressed nitrogen, which work together to dampen vertical loads and provide progressive resistance. The hydraulic fluid absorbs energy through flow restriction, while the nitrogen acts as a gas spring, storing and returning energy.

A servicing valve located at the upper end of the plunger tube allows for filling and pressure adjustments of both fluid and gas. A dynamic seal situated between the sliding and plunger tubes prevents fluid leakage during strut movement. This sealing interface is critical for maintaining pressure integrity under cyclic loading conditions.

This four-tube configuration enhances both shock absorption capability and steering responsiveness, especially during demanding ground operations. The integration of a rotating tube into the strut not only simplifies the overall geometry of the gear assembly but also minimizes the risk of mechanical interference between the damping and steering mechanisms.



## **2.2. Introduction to GD&T:**

Geometric Dimensioning and Tolerancing (GD&T) is a standardized framework used to define and communicate dimensional and geometric tolerances on technical drawings. It plays a central role in modern manufacturing by ensuring that parts are produced to meet functional requirements and can be assembled with consistency and precision.

The value of GD&T lies in its ability to eliminate ambiguity during the transition from design to production. By using a consistent symbolic language, engineers can specify not just the size of a feature, but also its allowable variation in form, orientation, and position. Without GD&T, manufacturers would face greater challenges in interpreting drawings, which increases the risk of errors, rework, and delays.

The GD&T system includes 14 fundamental geometric control symbols, covering features such as flatness, perpendicularity, parallelism, concentricity, and circularity. Understanding how and when to apply these symbols is essential for defining the true design intent and for enabling reliable inspection and quality assurance.

In practice, GD&T supports better communication between design, manufacturing, and quality control teams. It helps align expectations, reduces misinterpretation, and ultimately contributes to higher product quality and lower production cost. For these reasons, GD&T is not just a documentation tool – it is an integral part of engineering design methodology.

### ***2.2.1. Datum and datum reference frame:***

A datum can be represented as a theoretically exact plane, point, or axis from which other features of a part are referenced. Datums are used as references for dimensional tolerances.

The Datum Reference Frame (DRF) is one of the most important concepts in GD&T. The DRF outlines the formation of three theoretically perfect planes that are perpendicular to each other. These three planes are essential for the manufacturing and inspection of a part according to the drawing and are detailed as follows:

- **Primary datum** is established with at least three points of contact on the part's first feature.
- **Secondary datum** is established with at least two points of contact on the part's second feature.
- **Tertiary datum** is established with at least one point of contact.

The DRF is the "skeleton" of the geometric system – it is the reference frame from which all other geometric parameters are referenced, as well as the origin for all dimensions and related geometric parameters. The DRF creates six degrees of freedom (DOF), including three translational degrees of freedom and three rotational degrees of freedom. These DOFs must be constrained in the design, manufacturing, and inspection of parts. Parts are referenced to the DRF to allow for measurement, processing, and calculation.

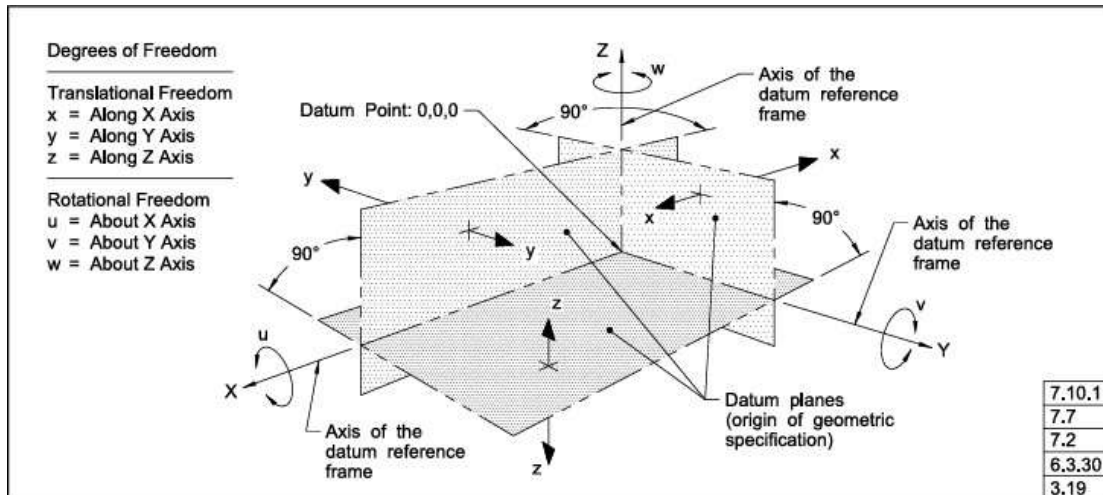


Figure 2.2. Datum Reference Frame

### 2.2.2. How GD&T works:

Geometric Dimensioning and Tolerancing (GD&T) defines how much variation is allowed for each design feature by specifying its nominal dimensions along with the permissible tolerance range. Tolerance is defined as the difference between the maximum and minimum acceptable limits for a given dimension. This range is essential for guiding manufacturing processes and ensuring parts fit and function as intended.





Effective tolerancing involves carefully selecting allowable deviations for each geometric feature, balancing the realities of production capability with the design's functional and visual requirements. Properly applied tolerances can improve manufacturing efficiency while maintaining the intended performance of the part.

GD&T symbols are used to clearly communicate these tolerances on technical drawings. They serve as a universal language between design, production, and inspection, helping to prevent misinterpretation and ensuring that each feature performs its intended role within the assembly.

### 2.2.3. GD&T symbols:

GD&T is feature-based, with each feature specified by different controls. Geometric tolerances are applied to features by feature control frames. GD&T symbols fall into five groups:

**a. Form control**

SYMBOL	GEOMETRIC CHARACTERISTICS	TYPE OF CONTROL
	Flatness	Form (No relation between the features) No Datum Reference Required
	Straightness	
	Cylindricity	
	Circularity (Roundness)	

(Source: Internet)

Form control specifies the shape of features, including:

- **Straightness:** Straightness is classified as either line element straightness or axis straightness. The requirement for straightness describes how straight a target must be. It is used for lines instead of planes, indicating a curve in the center line or generatrix. As a result, straightness is employed to express the warpage tolerance of lengthy objects.

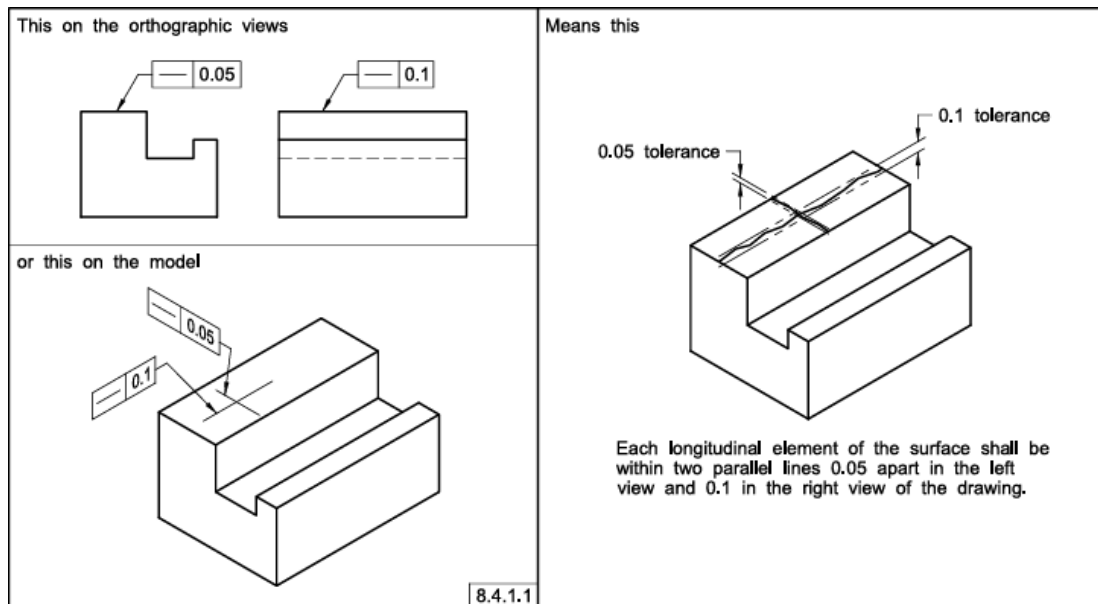


Figure 2.3. Specifying Straightness of a Flat Surface

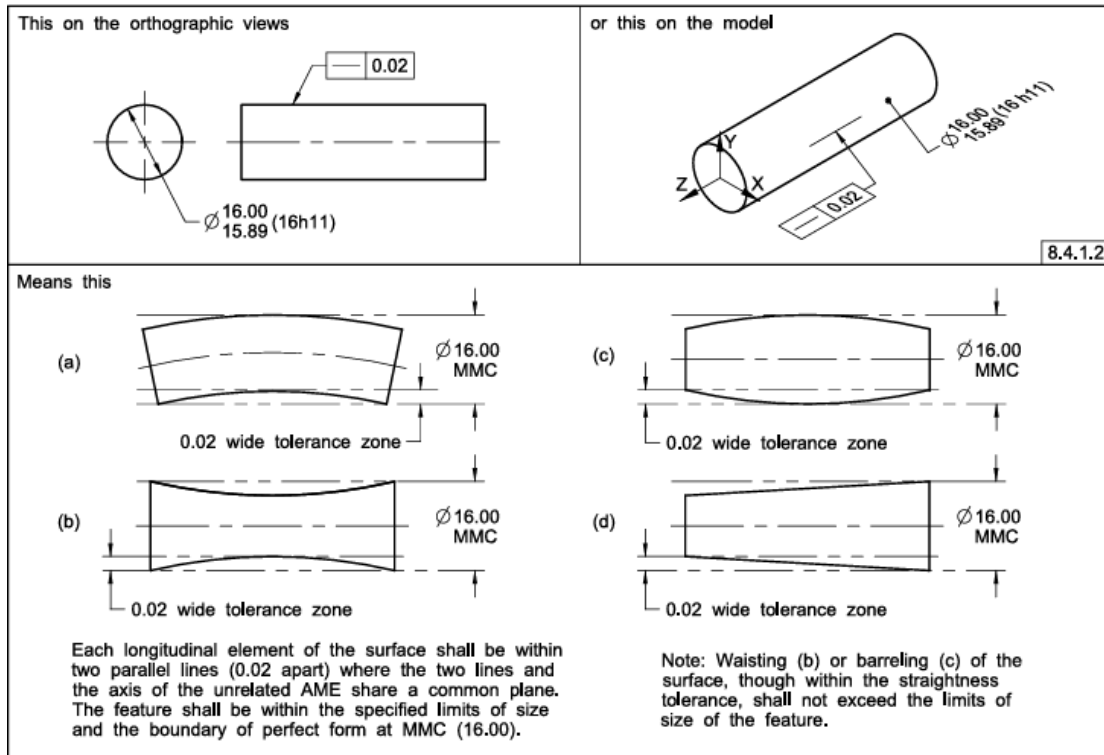


Figure 2.4. Specifying Straightness of Surface Elements

- **Flatness:** The flatness criterion states how even a surface or perfectly flat a target plane should be. The most protruding and concave parts must be located at a certain distance between two vertically separated planes. Flatness is often measured between a surface's highest and lowest points.

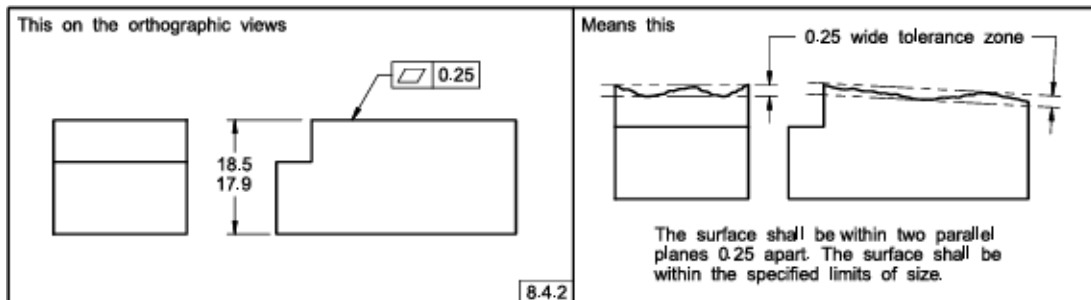


Figure 2.5. Specifying Flatness of a Surface

- **Cylindricity:** Cylindricity is the degree to which a feature must resemble a perfect cylinder. It consists of straightness, roundness, and taper, making it costly to check.

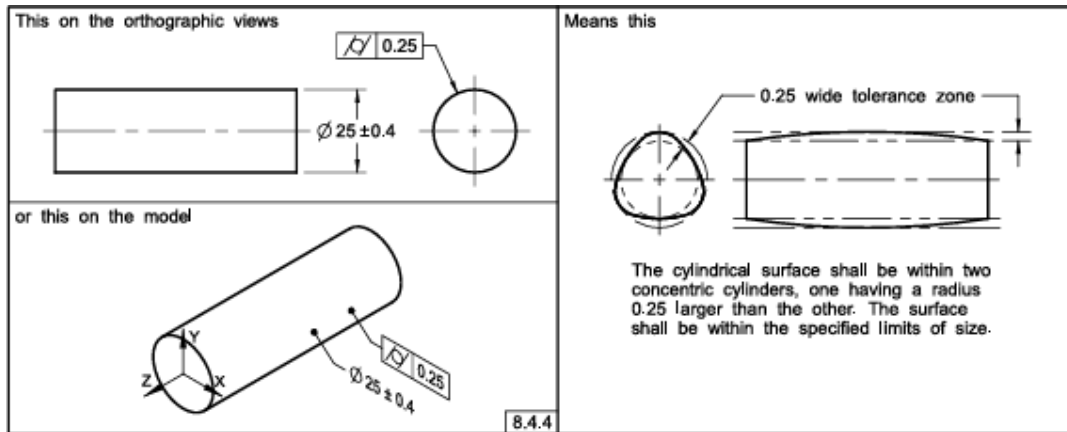


Figure 2.6. Specifying Cylindricity

- **Circularity or Roundness:** The roundness criterion describes how perfectly circular a target – the circular cross-section of a shaft, bore, or cone – must be. It also implies that the feature must be devoid of any characteristics or edges.

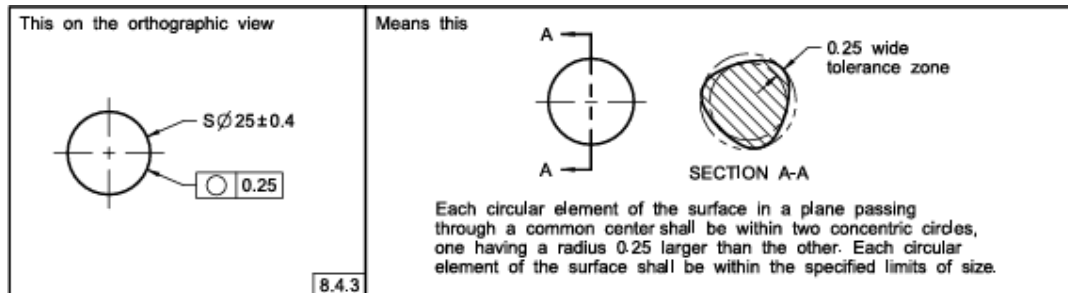


Figure 2.7. Specifying Circularity of a Sphere

## b. Orientation control

SYMBOL	GEOMETRIC CHARACTERISTICS	TYPE OF CONTROL
⊥	Perpendicularity	Orientation (No relation between the features)
//	Parallelism	Datum Reference Required
∠	Angularity	

(Source: Internet)

Orientation controls pertain to dimensions that change at angles, including:

- **Angularity:** Angularity is defined as flatness at an angle to a datum. And it is also determined by two reference planes spaced the tolerance value apart.

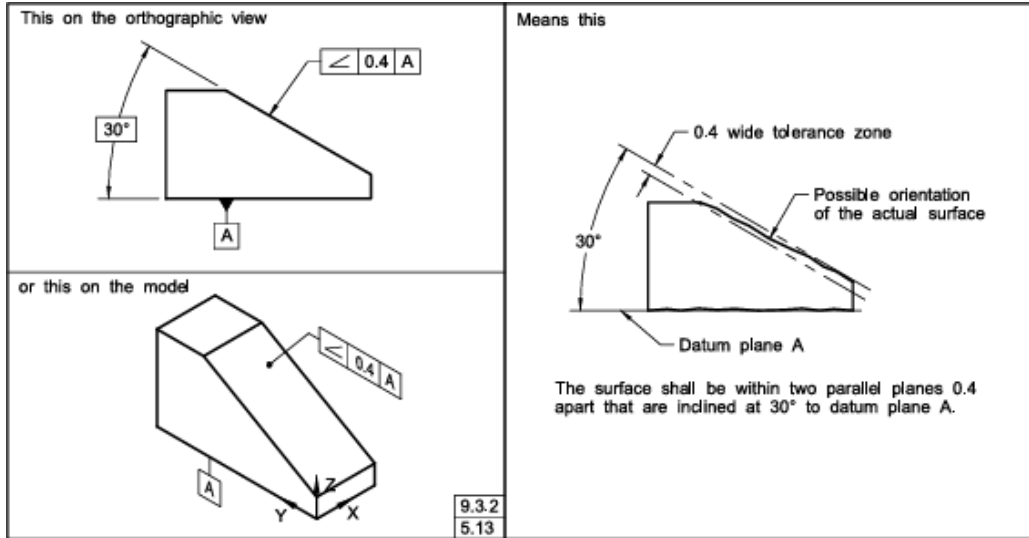


Figure 2.8. Specifying Angularity for a Plane Surface

- **Perpendicularity:** Perpendicularity indicates flatness at 90° to a datum. It requires two ideal planes between which the feature plane must lie.

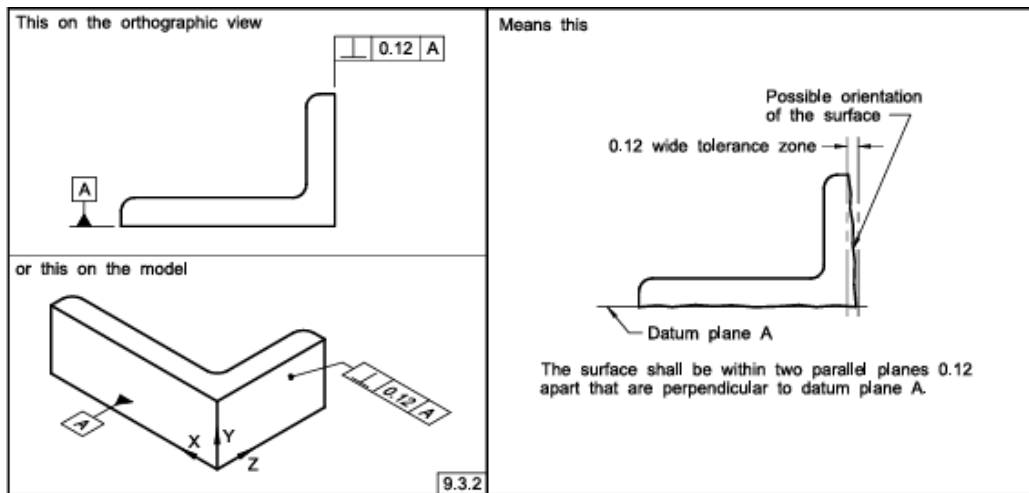


Figure 2.9. Specifying Perpendicularity for a Plane Surface

- Parallelism:** Parallelism denotes a parallel line at a specified distance. A cylindrical tolerance zone can be defined by inserting a diameter symbol in front of the tolerance value to define parallelism for axes.

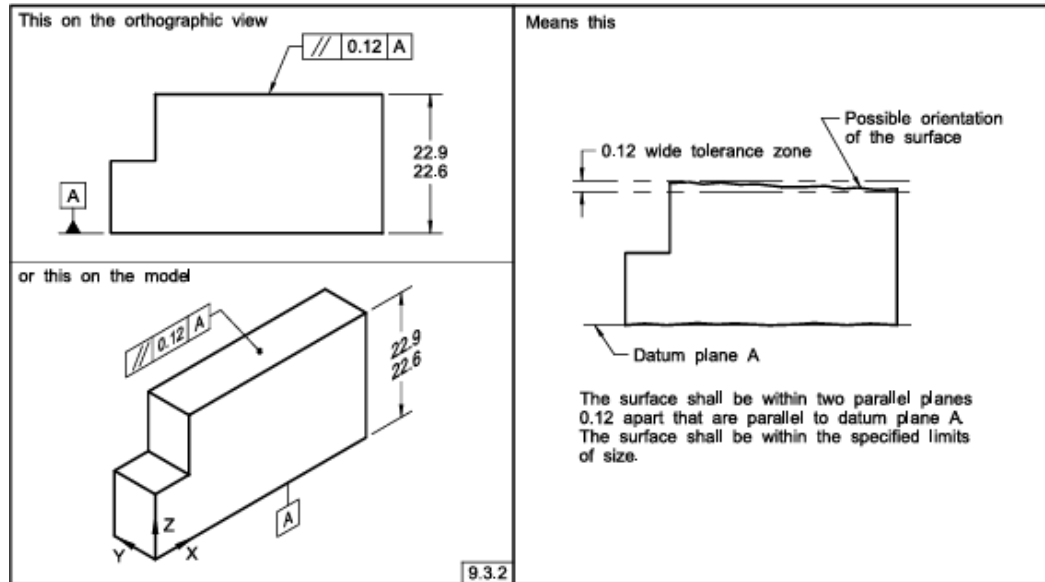


Figure 2.10. Specifying Parallelism for a Plane Surface

### c. Profile control

SYMBOL	GEOMETRIC CHARACTERISTICS	TYPE OF CONTROL
	Profile of A Surface	Profile
	Profile of A Line	

(Source: Internet)

Profile control describes the three-dimensional tolerance zone around a surface. It is further categorized into two, including:

- Line profile:** A line profile compares a cross-section in two dimensions to an ideal shape. Unless otherwise indicated, the tolerance zone is defined by two offset curves.

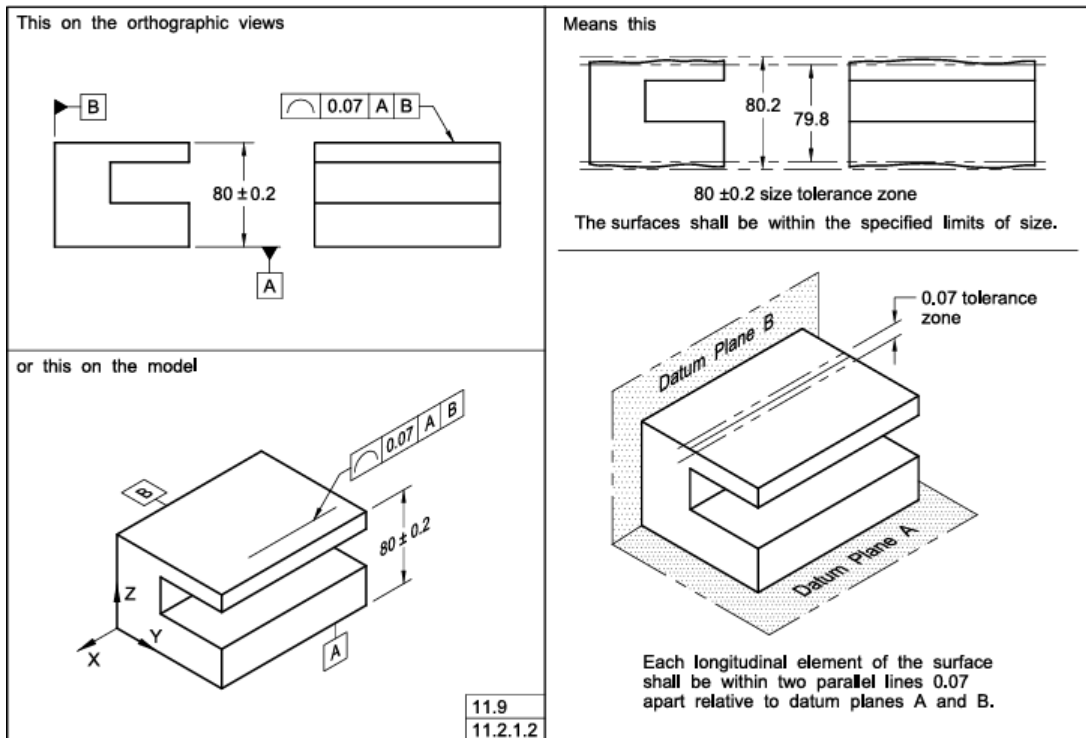


Figure 2.11. Profile of a Line and Size Control

- **Surface profile:** A surface profile is used to create two offset surfaces between which the feature surface must fall. Surface profile is a complicated control that is usually measured with a CMM.

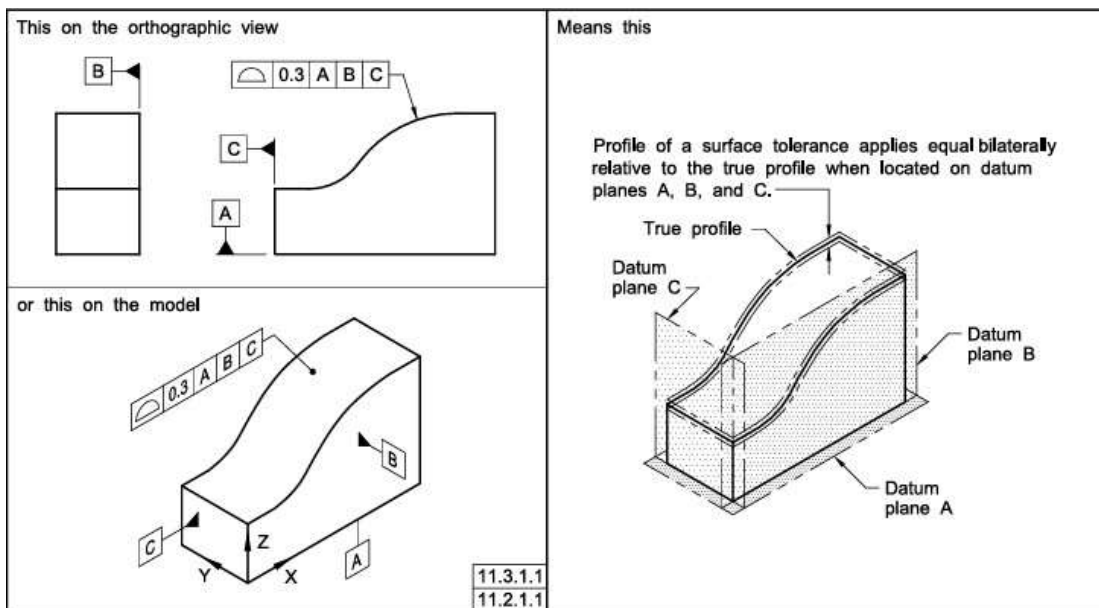



Figure 2.12. Profile of a Surface Application

#### d. Runout control




SYMBOL	GEOMETRIC CHARACTERISTICS	TYPE OF CONTROL
	Total Runout	Runout
	Circular Runout	

(Source: Internet)

Runout control indicates the amount by which a specific feature can vary to the datums:

- **Circular runout:** Circular runout is employed when it is necessary to account for various errors, such as those present in ball-bearing mounted parts. During the inspection, the part is rotated on a spindle to measure the variance or ‘wobble’ around the rotational axis.
- **Total runout:** Total runout is measured at numerous surface points, describing the runout of a circular feature and a whole surface. This controls changes in straightness, profile, angularity, etc

#### e. Location control

SYMBOL	GEOMETRIC CHARACTERISTICS	TYPE OF CONTROL
	Concentricity	Location
	Symmetry	
	Position	

(Source: Internet)

Location control uses linear dimensions to define feature locations:

- **Position:** Position specifies the location of features to the other or the datums and is the most commonly used control.
- **Concentricity:** The concentricity criterion specifies the concentricity’s accuracy of the axes of two cylinders (no deviation of the center). Concentricity compares the location of a feature axis to the datum axis.

- **Symmetry:** The symmetry requirement specifies the accuracy with which a target is symmetrical to the datum (reference plane). This helps to guarantee that there are no irregularities in your design's non-cylindrical sections. Symmetry is a complex control that is usually measured with a CMM.

#### 2.2.4. Feature control frame:

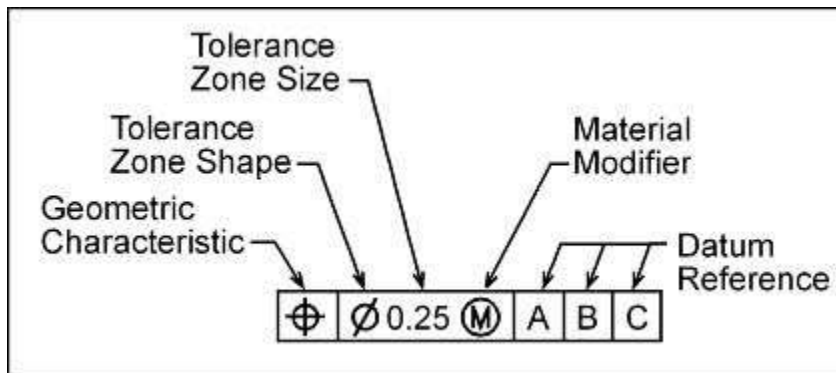


Figure 2.13. Feature Control Frame (Source: Internet)

In GD&T, a Feature Control Frame is a standardized rectangular box used to specify geometric tolerances applied to a specific feature on a part. It serves as the primary method for communicating how a feature should behave in terms of form, orientation, location, or runout.

Each feature control frame conveys a single geometric requirement. If a feature must meet multiple geometric requirements—such as both flatness and position—then separate frames are required for each.

A typical feature control frame is divided into three compartments:

- **First compartment:** Indicates the type of geometric control by showing one of the 14 standard GD&T symbols, such as straightness, perpendicularity, or position.
- **Second compartment:** Specifies the tolerance value for that geometric characteristic. If the feature has size (e.g., a hole or shaft), a material condition modifier like MMC (Maximum Material Condition) or LMC (Least Material Condition) may follow the tolerance value to define how size affects the allowed tolerance zone.

- **Third compartment:** Lists the datum features – reference geometries such as planes or axes – that establish the coordinate system for interpreting the tolerance.

**Material condition modifiers explained:**

In practice, geometric tolerances often depend on the size of a feature. For example, the allowable variation in position might be tighter or looser depending on whether the feature is at its smallest or largest size.

- **Maximum material condition (MMC):** This refers to the size at which a feature contains the greatest amount of material. For example, the smallest allowable hole or the largest allowable pin. MMC allows for bonus tolerance – more positional tolerance is permitted when the feature departs from MMC.
- **Least material condition (LMC):** The opposite of MMC; it represents the size at which the feature contains the least material (largest hole, smallest pin). LMC is used when clearance is critical or when structural minimums must be maintained.

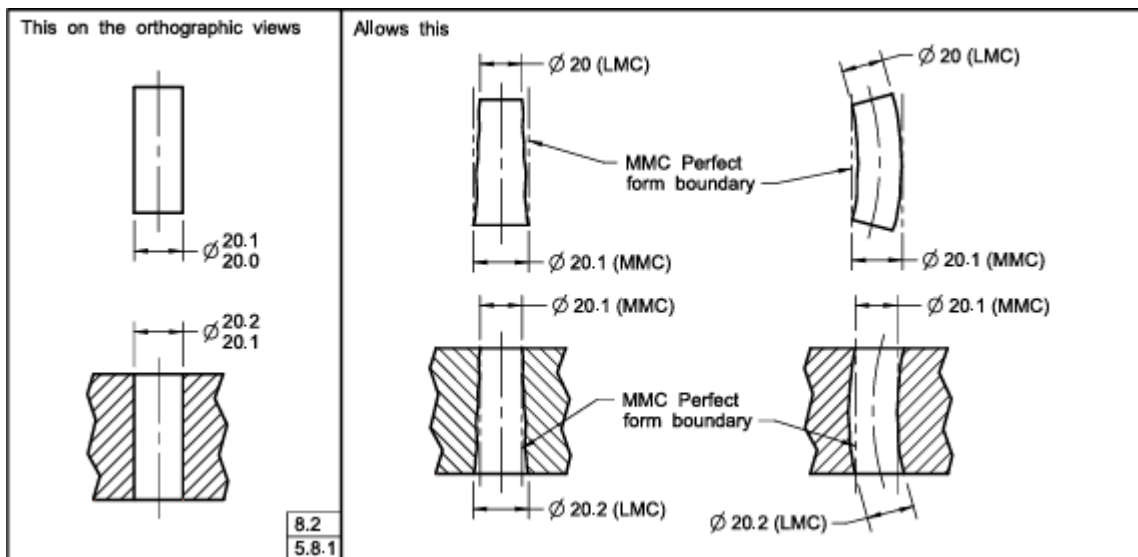


Figure 2.14. Material condition modifiers explained

Material condition modifiers help engineers link tolerance requirements to real-world part variability, allowing for greater flexibility in inspection and often improving manufacturability.

### **2.3. Theoretical background of finite element method and its application in structural analysis:**

To quantitatively assess the influence of geometric deviations on the stress distribution within the nose landing gear assembly – a system with complex geometry and contact interactions – classical analytical methods are insufficient. As such, this project adopts a numerical approach, specifically the Finite Element Method (FEM), as the core simulation technique. This section outlines the fundamental principles of FEM and key mechanical theories employed in the model.

#### ***2.3.1. Fundamentals of the finite element method (FEM):***

FEM is a numerical analysis technique used to obtain approximate solutions to problems governed by partial differential equations. The core idea of FEM is “divide and conquer”. Instead of solving for the entire structure analytically, FEM discretizes the structure into a finite number of simpler elements – such as tetrahedrons or hexahedrons in 3D – connected at nodes.

Within each element, physical quantities (e.g., displacement) are approximated using shape functions, typically low-order polynomials. Applying fundamental mechanical principles such as force equilibrium or energy conservation to the entire system leads to a set of algebraic equations in matrix form:

$$[K]\{u\} = \{F\}$$

Where:

[K] is the global stiffness matrix, assembled from individual element stiffness matrices, reflecting material and geometric properties.

{u} is the displacement vector (unknowns at the nodes).

{F} is the external load vector applied at the nodes.

Solving this matrix equation yields the nodal displacements. Strain and stress distributions inside each element can then be computed through interpolation based on the displacement field.

#### ***2.3.2. FEM workflow in structural simulation:***

The structural analysis process using FEM software (e.g., Abaqus) typically involves three major stages:

### **a. Preprocessing (Model setup):**

This stage determines the accuracy and reliability of the simulation:

- **Geometry modeling:** Import or create a 3D CAD model of the components—such as pins, torque links, and piston lugs.
- **Material properties definition:** Define mechanical properties (e.g., Young’s modulus, Poisson’s ratio) for each material used.
- **Meshing:** Discretize the model into finite elements. Mesh refinement is critical near stress concentration zones (e.g., hole edges, fillets, contact surfaces).
- **Boundary conditions & loading:** Specify constraints (e.g., fixed displacements) and apply loads (e.g., pressure or force). In this study, misalignment is simulated by assigning a prescribed displacement to specific nodes on the pin, representing geometric deviation.

### **b. Solving:**

Once preprocessing is complete, the solver generates the global stiffness matrix and solves for the displacement field using numerical methods. This step is computationally intensive.

### **c. Postprocessing:**

Engineers analyze simulation results using visual tools such as contour plots or animations. Key outputs include:

- Stress distributions (e.g., von Mises stress).
- Displacement and strain fields.
- Reaction forces at constrained nodes.

Accurate interpretation of these results is crucial to assess structural safety and performance.

### **2.3.3. Core theories applied in this study:**

To ensure the simulation reflects real-world conditions, the following mechanical theories are incorporated:

- **Static structural analysis:** The focus is on internal stress behavior under static loading. This approach is suitable for identifying stress concentrations caused by

geometric deviation, especially in critical joints, without accounting for transient dynamic effects.

- **Contact analysis:** In pin–hole assemblies, surfaces interact rather than merge. Contact modeling defines how surfaces engage under load. This includes normal behavior (e.g., “hard contact” to prevent penetration) and tangential behavior (e.g., frictionless assumption for simplification). Accurate contact definition is essential, especially when misalignment alters pressure distribution.
- **Von Mises yield criterion:** To evaluate material yield risk, the von Mises equivalent stress is calculated from the complex 3D stress state. A material is considered to yield when von Mises stress exceeds its yield strength. Color stress maps used in postprocessing visualize these values, helping identify critical zones.

## **2.4. Fundamental principles of solid mechanics and strength of materials:**

To correctly interpret results obtained from finite element analysis (FEA) – such as understanding stress distribution patterns or predicting structural failure – it is essential to have a solid grasp of the fundamental concepts in solid mechanics and material strength. This section outlines the theoretical foundations necessary for analyzing simulation outcomes in this project.

### **2.4.1. Stress and strain:**

When a structure is subjected to external forces, internal forces develop within the material to resist deformation. These internal responses are quantified by stress and strain.

- **Stress ( $\sigma$ ):** Stress measures the intensity of internal force over a unit cross-sectional area and is defined, for normal stress, as:

$$\sigma = P / A$$

Where:

P is the internal force perpendicular to the cross-section,

A is the cross-sectional area.

Stress is measured in Pascals (Pa), but in engineering practice, megapascals (MPa) are more common (1 MPa =  $10^6$  Pa). In complex loading conditions, stress is a second-order tensor comprising both normal and shear components.

- **Strain ( $\epsilon$ ):** Strain quantifies the relative deformation of a body. For axial loading:

$$\epsilon = \Delta L / L_0$$

Where:

$\Delta L$  is the change in length,

$L_0$  is the original length.

Strain is a dimensionless quantity.

#### **2.4.2. Stress–Strain Relationship and Material Properties:**

Each material has a unique stress – strain behavior, typically obtained from tensile testing.

- **Elastic region and Hooke’s Law:** In the initial phase of loading, most engineering materials behave elastically. Stress is proportional to strain:

$$\sigma = E \times \epsilon$$

Where E is the Young’s modulus, indicating material stiffness. A higher E implies less deformation under the same stress. This value must be defined in simulation tools like Abaqus.

The Poisson’s ratio ( $\nu$ ) describes the lateral contraction when a material is stretched longitudinally.

- **Yield point and plastic deformation:** When stress exceeds the yield strength ( $\sigma_y$ ), the material undergoes permanent (plastic) deformation. This transition is critical in mechanical design as it marks the boundary between safe operation and potential failure.

#### **2.4.3. Stress Concentration:**

In practice, components often include holes, notches, or steps that disrupt the uniform flow of internal forces. These geometric discontinuities cause localized stress amplification, known as **stress** concentration.

The severity is characterized by the stress concentration factor ( $K_t$ ):

$$\sigma_{\max} = K_t \times \sigma_{\text{nom}}$$

Where:

$\sigma_{\text{nom}}$  is nominal stress,

$\sigma_{\text{max}}$  is peak local stress.

In complex geometries, analytical calculation of  $K_t$  is impractical. FEA eliminates this need by directly computing stress fields across the model, revealing high – stress regions visually – often seen as red zones in simulation results.

#### **2.4.4. Strength theories for safety evaluation:**

Under multi-axial loading, multiple stress components coexist at a point. To assess failure risk, a scalar equivalent stress is needed to compare against  $\sigma_y$ .

- The von Mises yield criterion is widely used for ductile materials like steel and aluminum. It posits that yielding begins when the distortional energy reaches a critical threshold equivalent to that of a uniaxial tensile test.

The Von Mises equivalent stress is given by:

$$\sigma_v^M = \sqrt{\frac{1}{2} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}$$

Where  $\sigma_1, \sigma_2, \sigma_3$  are the principal stresses.

- Safety condition:

$$\sigma_v^M \leq \sigma_y$$

If this condition is satisfied, the material remains in the elastic regime and operates safely.

## Chapter 3

### **3D MODELING OF NOSE LANDING GEAR ASSEMBLY IN CATIA**

#### **3.1. Introduction to CATIA software:**

CATIA is a state-of-the-art 3D modeling software developed by Dassault Systèmes, a prominent French technology corporation specializing in aerospace, industrial design, and systems engineering. As a multi-disciplinary platform, CATIA seamlessly integrates CAD (Computer-Aided Design), CAM (Computer-Aided Manufacturing), and CAE (Computer-Aided Engineering), offering an end-to-end solution from concept to production.

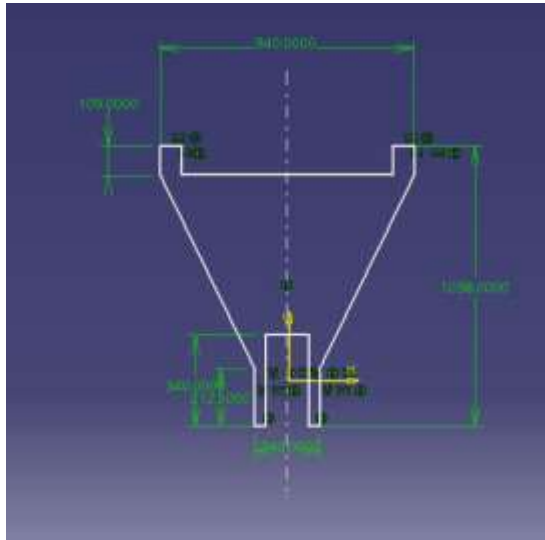
In the aerospace sector, CATIA plays a critical role in the precise and detailed modeling of complex mechanical assemblies, notably landing gear systems. Its strengths in parametric modeling, multi-part assembly, tolerance control, and kinematic simulation empower engineers to ensure design integrity and manufacturability at every stage.

Beyond 3D solid modeling, CATIA enables the creation of complete 2D technical drawings – including orthographic projections, section views, and detailed views – with full bi-directional associativity. Any modification to the 3D model is automatically reflected in the drawing sheets, and vice versa, maintaining consistency throughout the project lifecycle. CATIA is not just a design tool – it is the bridge between engineering vision and manufacturing reality.

#### **3.2. 3D modeling workflow in CATIA:**

##### **3.2.1. Forestay:**

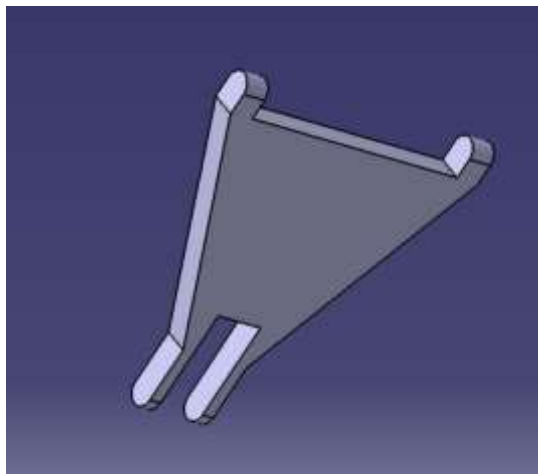
- Begin by creating the front profile of the forestay using the **Sketch** tool on the appropriate reference plane.



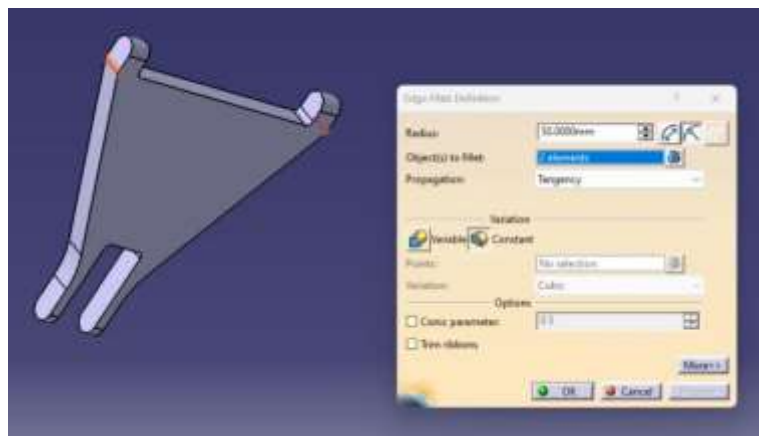
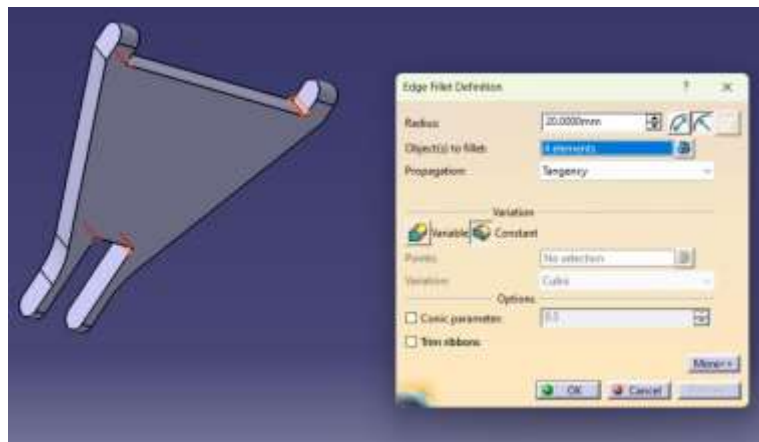
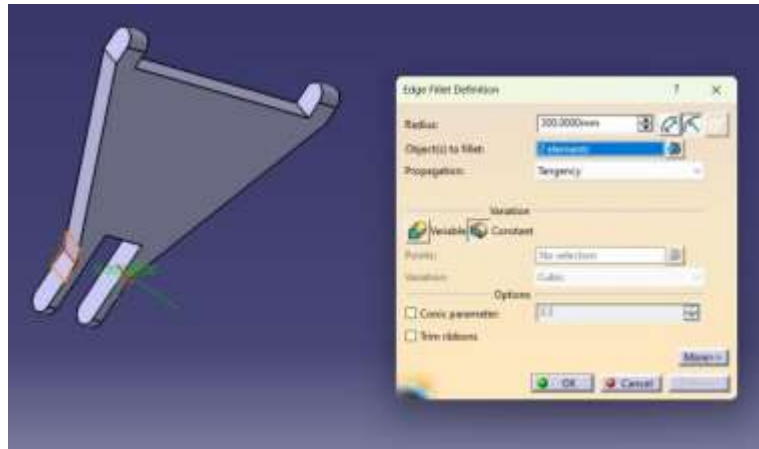
- Use the **Pad** command to extrude the 2D sketch into a 3D base shape. Next, draw the side profile of the forestay to define its lateral boundary.



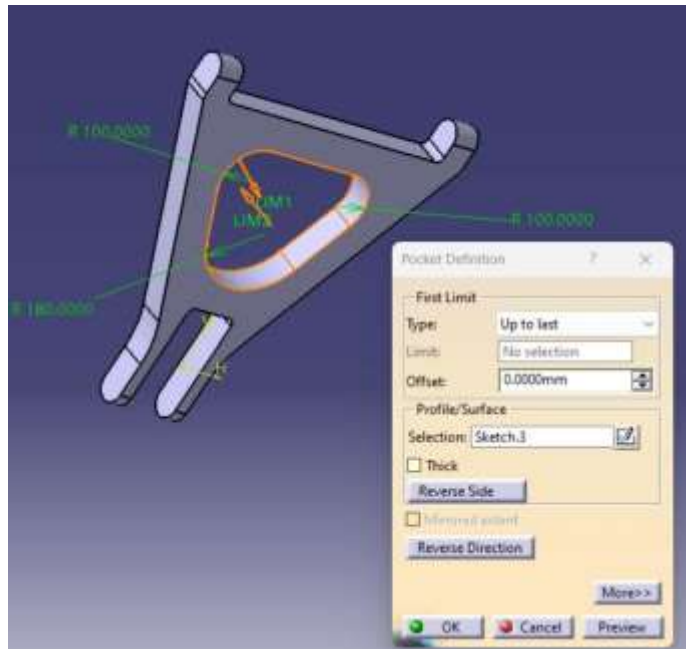
- Apply the **Pocket** function to remove excess material outside the desired side profile, forming the preliminary geometry of the part.



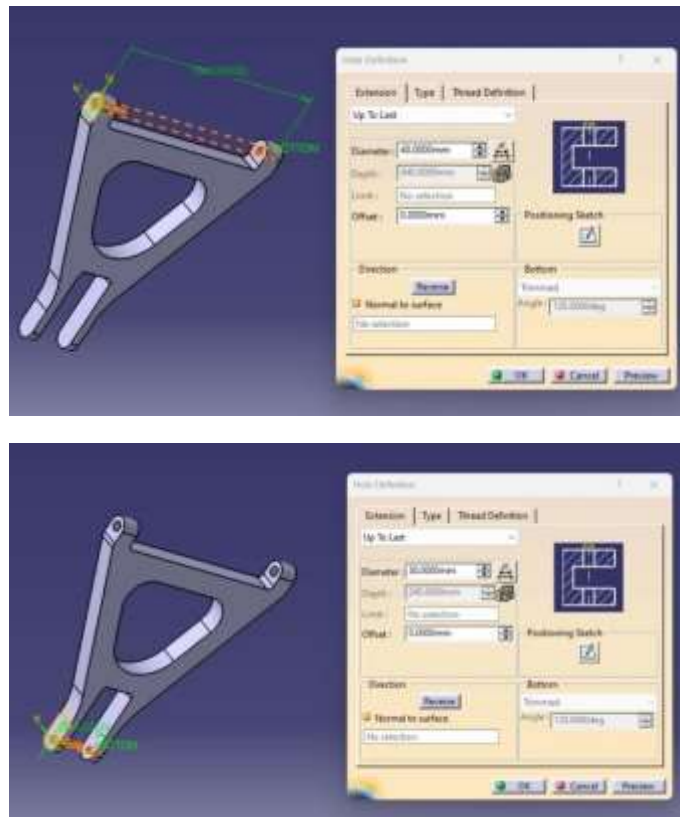
- Use the **Fillet** command to round off sharp edges at appropriate locations for smoother transitions.



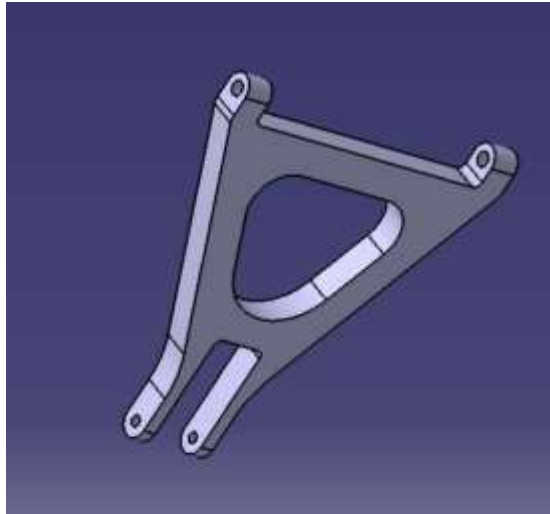
- Additional grooves are modeled using the **Pocket** tool.



- Holes are added at predefined positions using the **Hole** function.

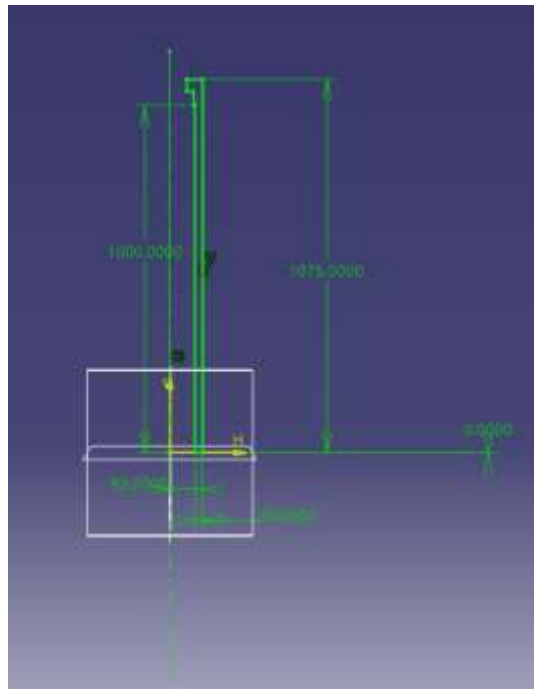


- The final geometry of the forestay is completed after these operations.

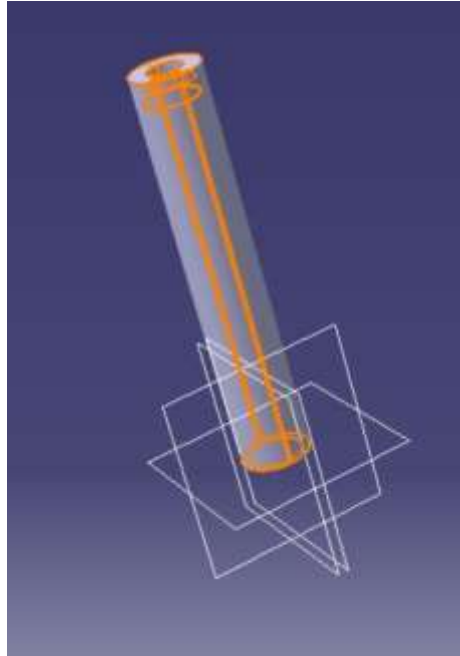


### **3.2.2. Shock strut:**

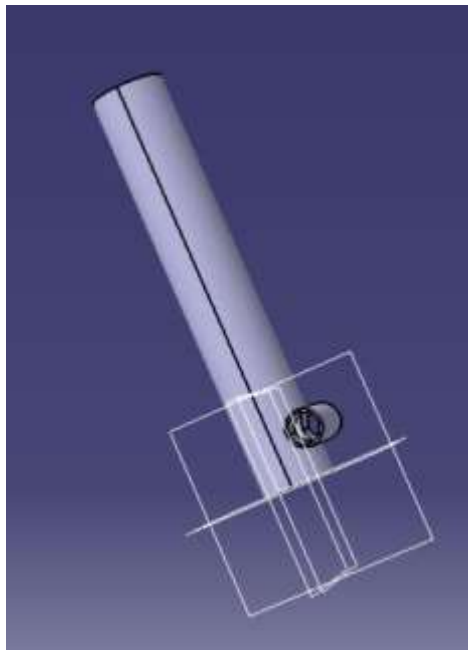
- Start by sketching the cross-sectional profile of the shock strut.



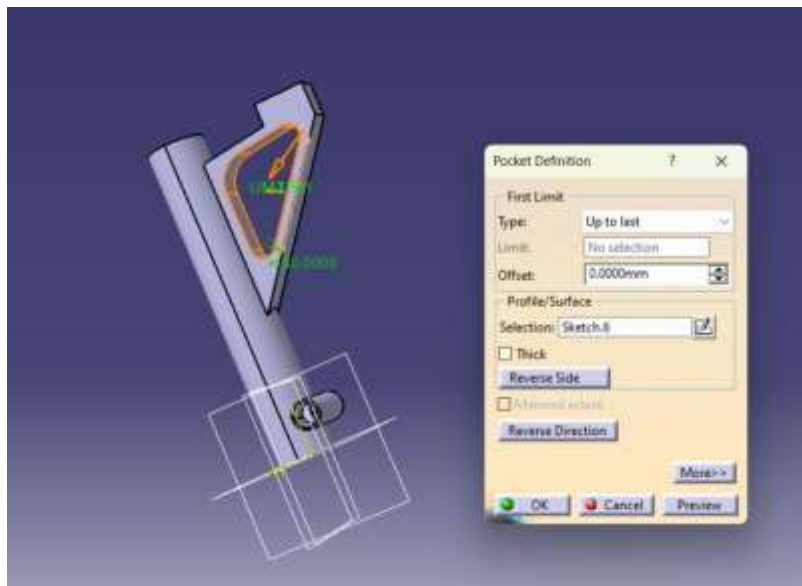
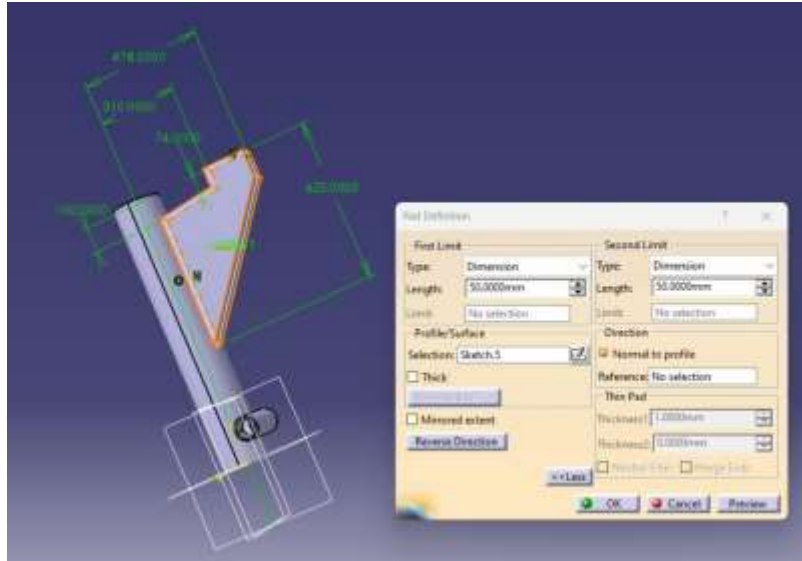
- Use the **Shaft** command to generate a revolved solid based on the profile.



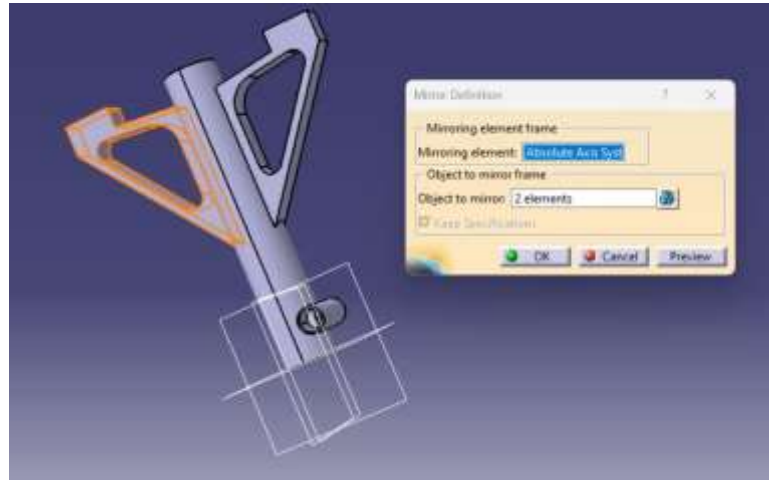
- A secondary cylindrical section adjacent to the main strut is created using a similar sketch and revolve approach.



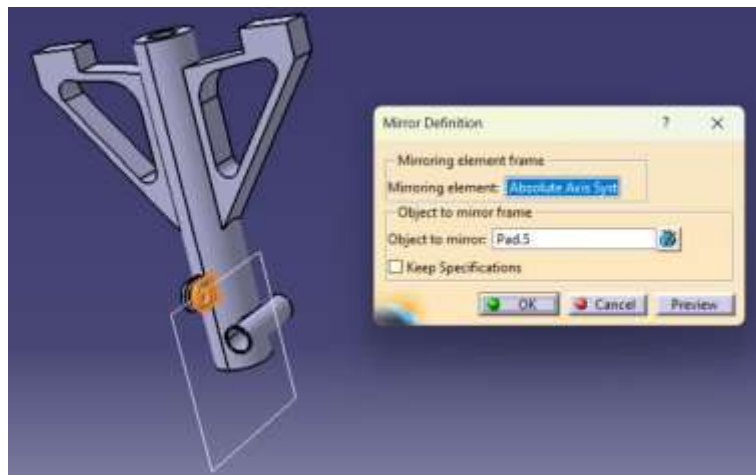
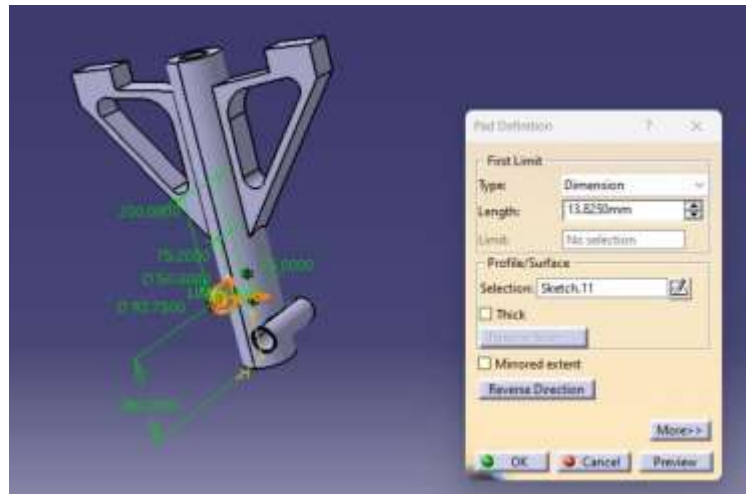
- The lateral features of the shock strut are modeled next, again following the sketch–shaft method.



- Use the **Mirror** function to replicate symmetrical features across the central plane.



- Two symmetric **lugs** are created in the same manner, ensuring proper alignment and geometry.

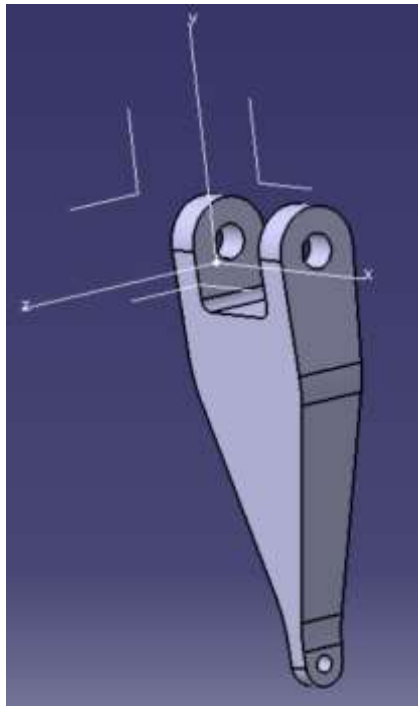




- Use the **Pocket** tool to remove material along the side profile and refine the overall shape.

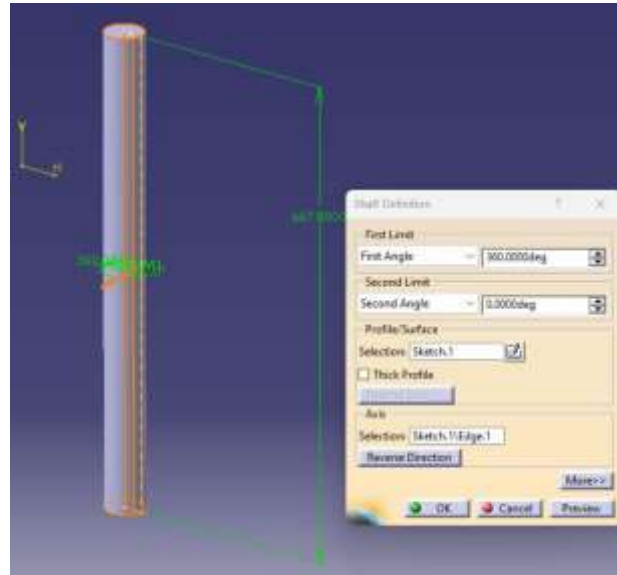


- Apply **Fillet** to smooth corners and **Hole** to add necessary mounting holes at designated locations. The final model represents a clean and fully defined torque link component.

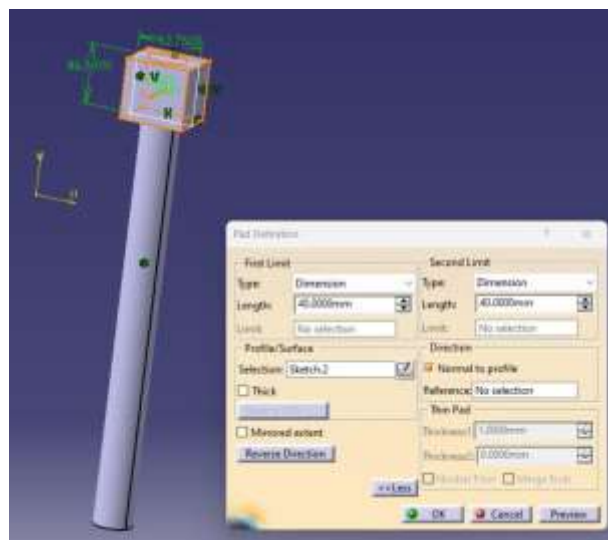


### 3.2.4. Tubular arm:

- Begin by revolving a circular sketch to create the main cylindrical body using the **Shaft** command.



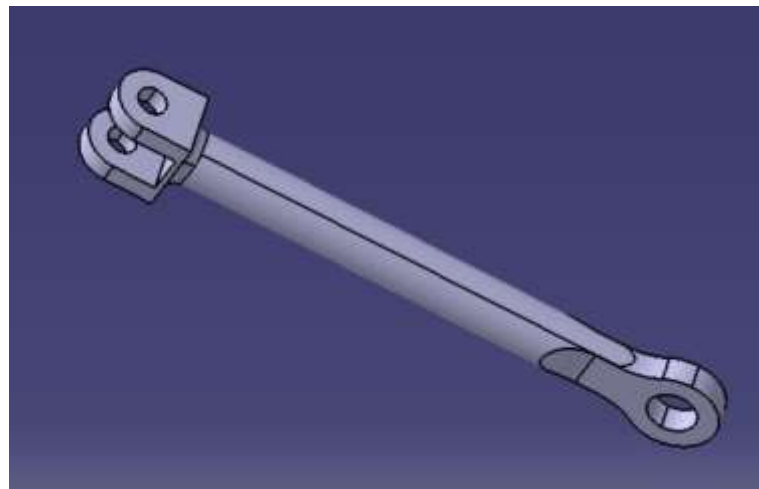
- Create a rectangular prism at one end of the arm to represent the connecting block.



- Use basic Boolean operations and sketch-based cuts to shape the part further.

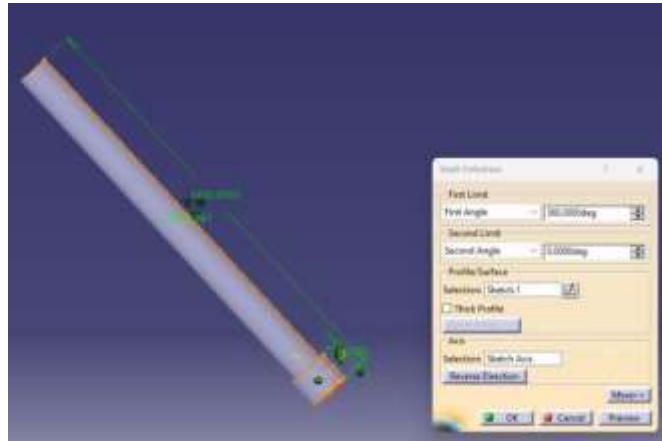


- Final detailing (e.g., edge rounding, hole placement) completes the model.



### 3.2.5. Sliding tube:

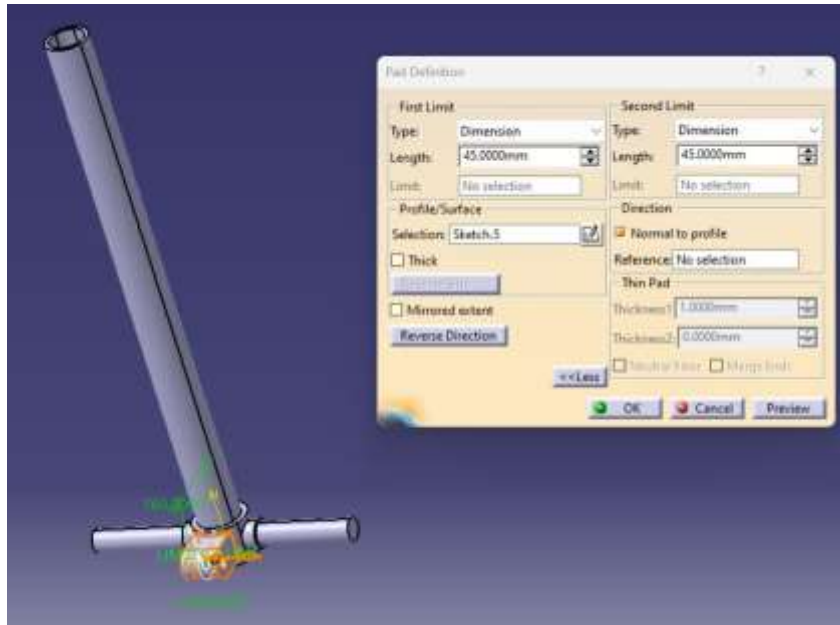
- Start with a revolved base body using the **Shaft** tool, based on a defined axial sketch.



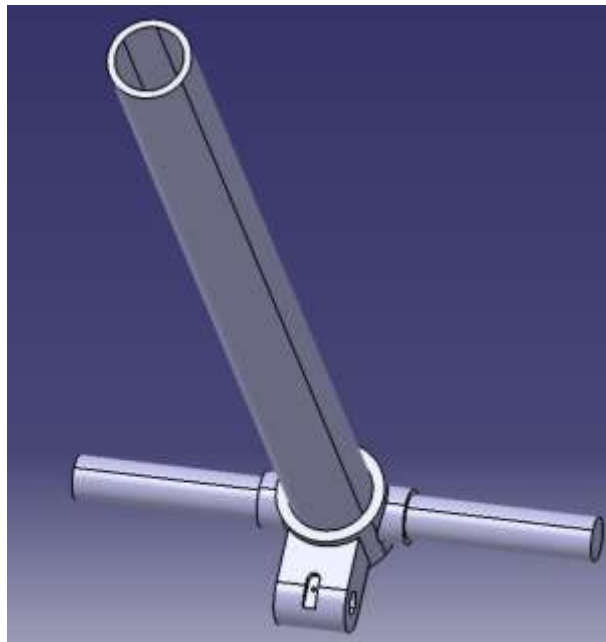
- Generate the side tubular extensions using additional sketches and revolved features.



- Create **lugs** for attachment to the torque link using similar sketch–pad or pocket techniques.

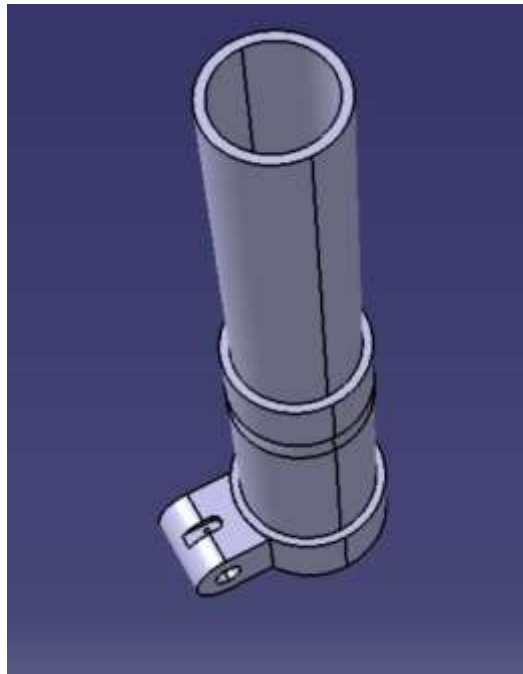
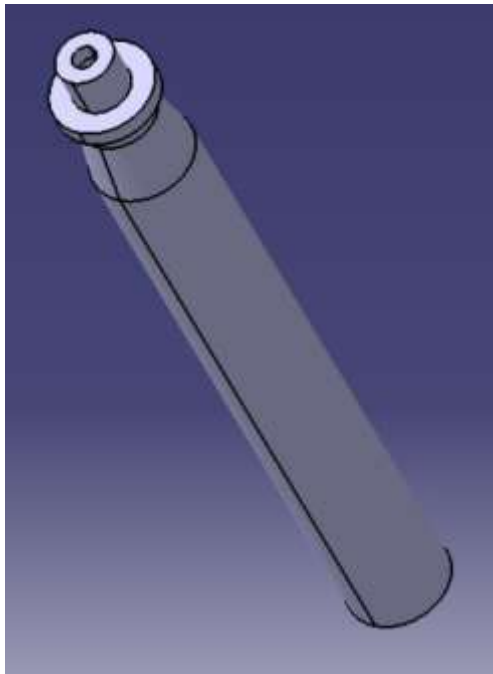
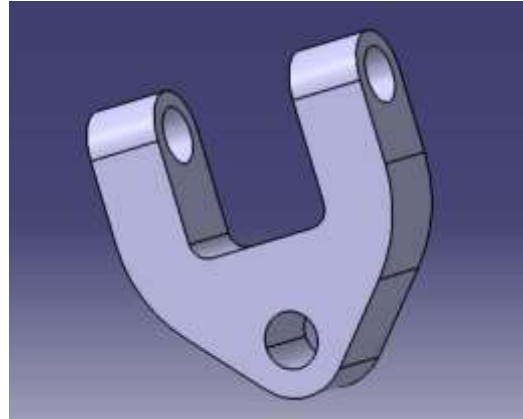
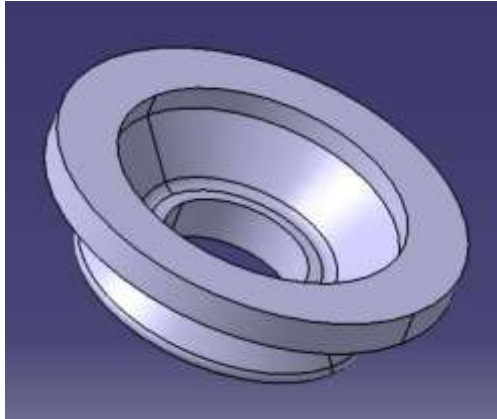


- Final fillets and holes are added to complete the sliding tube geometry.



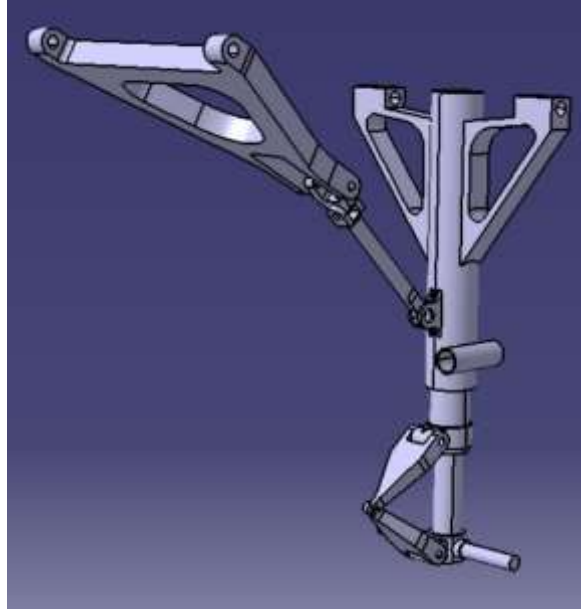
### **3.2.6. Other components:**

- Design each part individually following similar processes: sketching, extrusion, cutting.
- Assign material and physical properties to each component.



### **3.2.7. Nose landing gear assembly:**

- Using the individual components previously modeled, we proceed to the **Assembly Design** workbench in CATIA. Within this environment, all parts are imported and accurately constrained to form the complete **Nose Landing Gear (NLG) assembly**.



## Chapter 4

### **DESIGN OF ASSEMBLY PROCESS**

#### **4.1. Definition of assembly process design:**

- Assembly technology plays a crucial role in the production process of mechanical products. A complete product is typically composed of multiple individual components, each manufactured through machining or other processing methods. Once these parts meet the required specifications, they are assembled into functional units or finished products.
- Assembly is the final stage of production, and it has a decisive impact on the overall quality and operational stability of the product. Only after successful assembly does the product attain its intended utility and economic value.
- Even when individual parts are fabricated with high precision, an improper assembly process – such as incorrect sequence, poor fit control, or the use of unsuitable assembly methods – can significantly degrade the product's performance and durability. Therefore, assembly technology not only ensures dimensional and positional accuracy but also contributes to product longevity and operational efficiency.

#### **4.2. Basic principles of assembly process design:**

- Compliance with product functional requirements: The assembly sequence and methods must preserve the functional characteristics of the product
- Technological feasibility: The process must be feasible under actual workshop conditions, considering accessibility, manual handling and tooling.
- Follow the "inside – out", "bottom-up", "small – to – large" principles: Assembly should begin with internal components, then progress to outer assemblies, minimizing disassembly and rework.
- Optimize operation count and reduce handling time: The number of operations and steps should be minimized while maintaining quality, which helps reduce overall production time and costs.
- Select assembly methods based on joint characteristics.

- Facilitate inspection and maintenance: The process should incorporate clear inspection steps at critical stages, and allow for easy disassembly for maintenance purposes after assembly is completed.

#### **4.3. Basic assembly method:**

In modern mechanical manufacturing, selecting an appropriate assembly method plays a crucial role in ensuring product quality, precision, and productivity. Below are the commonly used basic assembly methods:

- Full Interchangeability Method: All parts are manufactured with high precision, allowing them to fit into any position without adjustment.
  - Advantages: High productivity, simple operations, no need for highly skilled workers.
  - Disadvantages: Depends heavily on machining precision and tolerance chain control.
  - Suitable for: Mass production.
- Limited Interchangeability Method: Allows for looser tolerances but may result in a certain rejection rate. Used for assemblies with multiple steps and high accuracy requirements.
- Selective Assembly Method: Parts are measured and grouped by size before assembly to ensure proper fit.
  - Advantage: Reduces machining precision requirements, lowers cost.
  - Disadvantage: Increases inspection and storage costs.
- Fitting (Compensational) Assembly Method: The compensating part is machined during assembly to achieve the desired fit. Avoid selecting compensation parts at the intersection of two tolerance chains.
- Adjustable Assembly Method: Accuracy is achieved by adjusting the position or size of auxiliary parts.
  - Convenient for repair and restoring accuracy over time.
  - Suitable for unit or small batch production.

#### **4.4. Forms of assembly organization:**

##### **4.4.1. Stationary assembly:**

The assembly object remains stationary while components and workers move to it.

- **Centralized:** All operations are performed at a single location.  
Suitable for large, heavy products or one – off production.
- **Decentralized:** Subassemblies are completed at separate stations and brought together later.  
Improves productivity, suitable for medium-scale production.

#### ***4.4.2. Moving assembly:***

The product moves through various stations, each performing specific tasks.

- **Free-moving:** Movement is uncoordinated and not cycle-based (e.g., by carts, cranes).
- **Flexible,** suitable for varied production.
- **Forced-moving/Assembly Line:** Moves in a fixed rhythm using conveyor belts or chain systems.

Requires full interchangeability, balanced task distribution, timely material supply.

Ideal for mass production.

#### **4.5. Design of assembly process:**

##### ***4.5.1. Preliminary assembly process of the nose landing gear:***

Step 1: Install the completed piston assembly into the sliding tube

Step 2: Install the turning tube into the shock strut

(Insert the turning tube (integrated with piston) into the main shock strut body.)

Step 3: Insert the sliding tube into the turning tube

(Slide the sliding tube into the turning tube and ensure smooth movement without jamming.)

(Verify full stroke range from fully compressed to extended positions.)

Step 4: Secure the piston valve head to the top of the shock strut

(Secure the valve (attached to piston) with the top cap of the shock strut using locking ring or threaded coupling.)

Step 5: Connect the tubular arm to the forestay through the universal joint

(Attach the upper end of the tubular arm to the forestay via a universal joint and secure with pin/bolt.)

Step 6: Install the Tubular Arm – Forestay assembly onto the shock strut

(Align and attach the other end of the tubular arm to the shock strut body via hinge or connecting bolt.)

#### ***4.5.2. Torque Link center hinge assembly process (with lock plate):***

Step 1: Install washer on shaft:

- Ensure chamfer in washer is on head side of shaft.



Figure 4.1. Assembly Process – Step 1

Step 2: Align center bores of upper and lower torque-link arms and install washer.

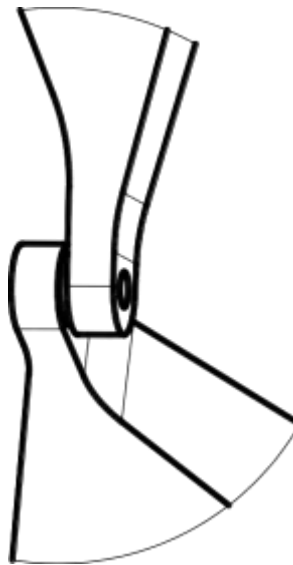


Figure 4.2. Assembly Process – Step 2

Step 3: Install shaft and washer into torque-link assembly:

- Can insert from right or left side.

- Do not use a hammer; use jack if necessary.

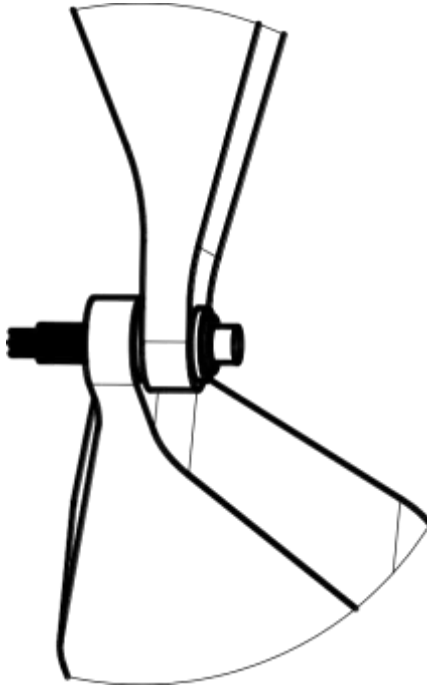


Figure 4.3. Assembly Process – Step 3

Step 4: Install washer on shaft:

- Ensure splines correctly engage.
- Washer must touch torque-link arm.

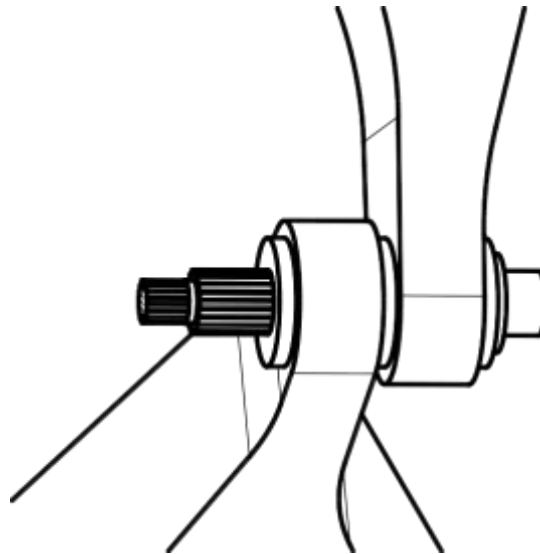


Figure 4.4. Assembly Process – Step 4

Step 5: Hold shaft (1) and install nut (5).

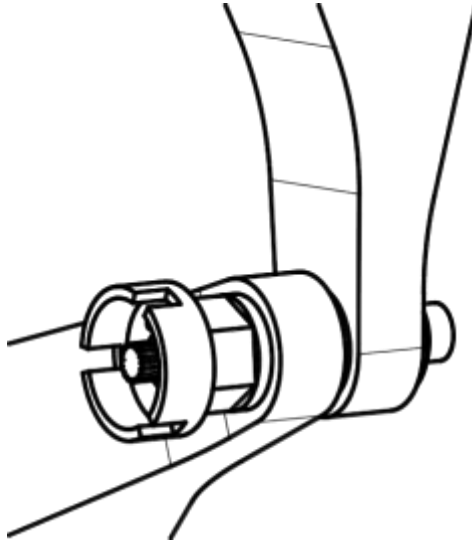


Figure 4.5. Assembly Process – Step 5

Step 6: Tighten nut and align lock plate as follows:

CAUTION: DO NOT use a wrench – tighten by hand only!

- Loosen and retighten by hand to remove gaps.
- Put the lock plate in position into the nut.
  - Ensure lock plate lugs engage correctly in nut slots.
- Align lock plate and nut holes.

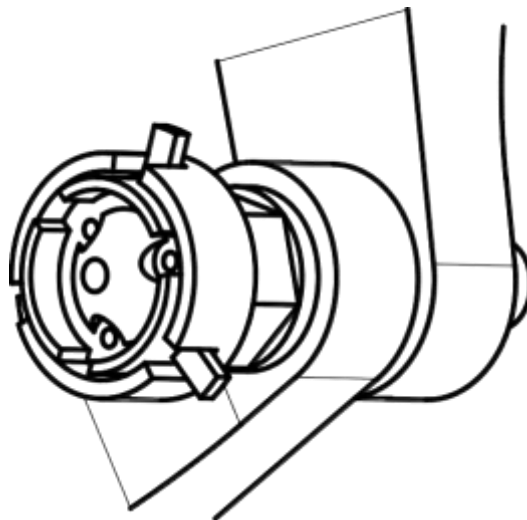


Figure 4.6. Assembly Process – Step 6

Step 7: Install bolt (7).

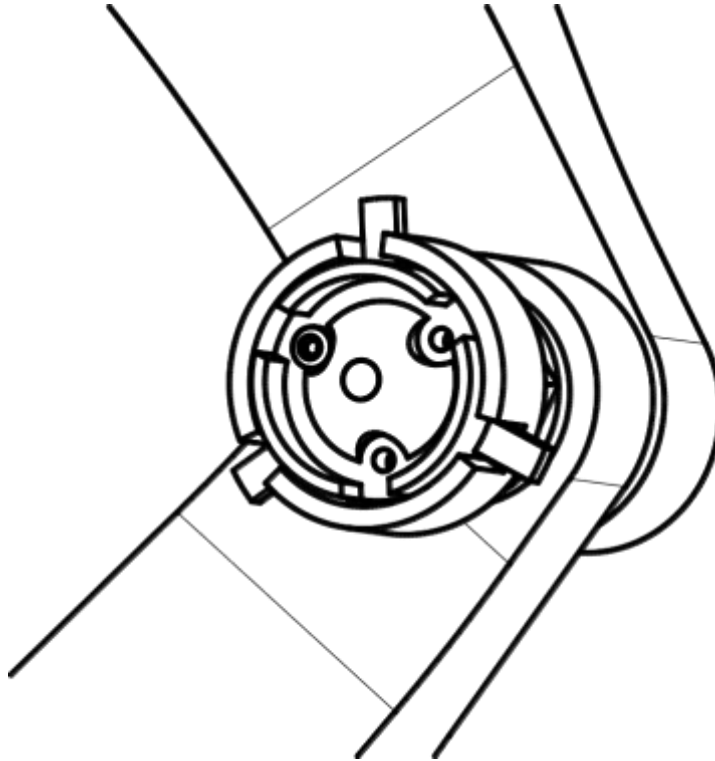


Figure 4.7. Assembly Process – Step 7

Ensure shaft rotates freely by hand:

- If not rotatable on ground:
  - Raise nose gear per AMM TASK 07-11-00-581-003.
  - Repeat hinge installation process.

Step 8: Secure bolt using lockwire or safety cable through bolt and lock plate.

- Twist wire ends securely in lock plate hole.

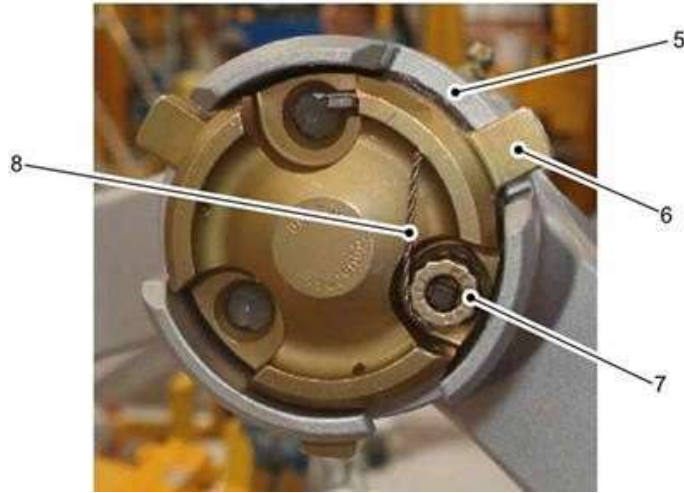


Figure 4.8. Install of the safety cable

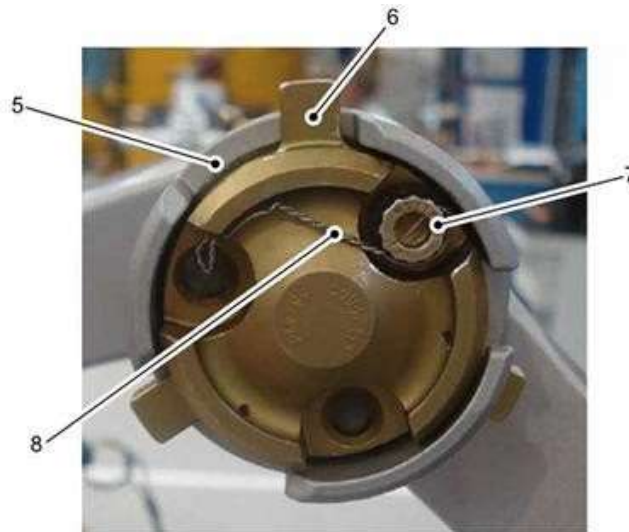


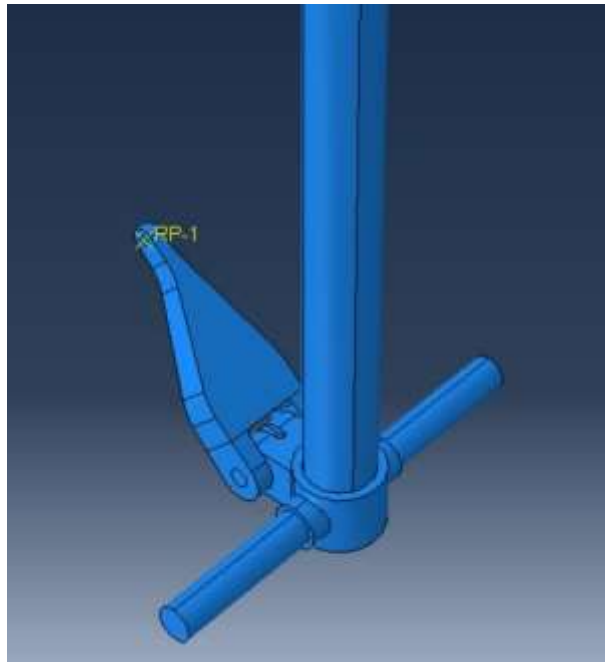
Figure 4.9. Install of the lockwire

## Chapter 5

### **SIMULATION OF GD&T EFFECTS ON STRESS DISTRIBUTION**

#### **5.1. Case study description:**

To evaluate the impact of Geometric Dimensioning and Tolerancing (GD&T) – specifically, the effect of parallelism deviation between the hole and the fitted pin – we selected a representative assembly consisting of three components, as illustrated.



**Objective:** To observe the variation in stress distribution within the components under different levels of misalignment.

The misalignment was simulated as follows: the assembly of three components was modeled, with one end of the pin fixed and the other subjected to a boundary condition that induces displacement. This setup represents a misalignment scenario resulting from assembly inaccuracies.

Simulation cases:

- Case 1 (baseline): 0 mm parallelism deviation
- Case 2: 0.001 mm deviation
- Case 3: 0.002 mm deviation
- Case 4: 0.005 mm deviation

- Case 5: 0.008 mm deviation
- Case 6: 0.01 mm deviation
- Case 7: 0.02 mm deviation
- Case 8: 0.05 mm deviation
- Case 9: 0.08 mm deviation
- Case 10: 0.1 mm deviation
- Case 11: 0.2 mm deviation
- Case 12: 0.5 mm deviation
- Case 13: 0.8 mm deviation
- Case 14: 1.0 mm deviation

## **5.2. Material selection:**

### **5.2.1. Overview of materials for aircraft landing gear:**

- Landing gear components are required to operate under harsh environments and withstand various types of loads and conditions. These include significant impact forces during landing, repetitive loading during service life, and exposure to environmental factors that may cause corrosion and material degradation. At the same time, the aerospace industry prioritizes weight reduction to improve fuel efficiency and payload capacity, without compromising structural integrity or safety.
- Main material groups used in civil aircraft landing gear:
  - **High-strength steel alloys:** Known for their superior strength, stiffness, and toughness, typically used in heavily loaded structural parts.
  - **Aluminum alloys:** Popular for their high strength-to-weight ratio and good corrosion resistance.
  - **Titanium alloys:** Provide an excellent balance of high strength, low weight, and outstanding corrosion resistance, making them ideal for performance-critical and long-life applications.
- In addition, the use of **composite materials** for certain landing gear components is receiving increasing attention due to their high strength-to-weight ratio and potential for fuel efficiency improvements. However, composites are currently less common in primary load-bearing structures such as tubes and braces compared to metallic alloys.

### 5.2.2. Material data used:

- Material for Torque link

Material	Elastic Modulus (GPa)	Poisson's Ratio	Density (kg/m <sup>3</sup> )	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
300M steel	205	0.28	7870	1586	1931

- Material for Pin and Sliding tube

Material	Elastic Modulus (GPa)	Poisson's Ratio	Density (kg/m <sup>3</sup> )	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
A7075 - T6	71.7	0.33	2810	503	572

### 5.3. Simulation setup:

#### 5.3.1. Abaqus software overview:

Abaqus is a product of Dassault Systèmes, a France-based technology and software company. It was developed in the 1970s in response to increasing demand for computational tools in engineering analysis and simulation. Since then, it has evolved into one of the leading engineering simulation platforms globally.

Abaqus is widely used in mechanical engineering, civil engineering, and related fields. It allows users to simulate and analyze structures, components, and processes to assess performance, durability, and interactions among system elements.

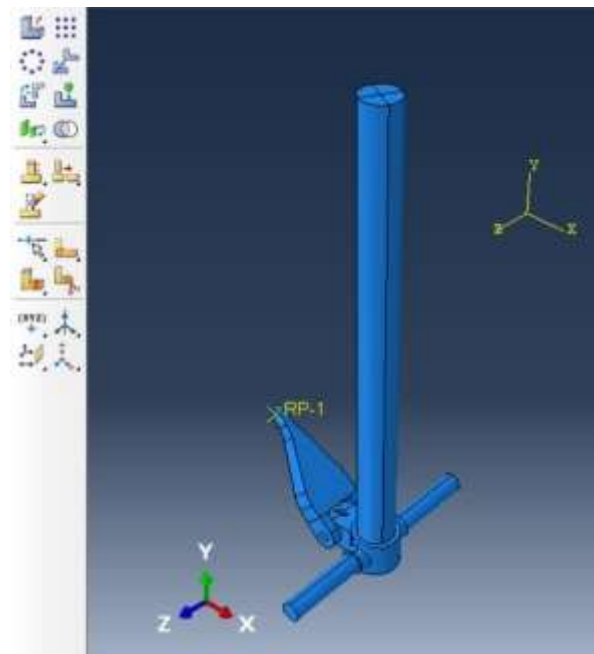
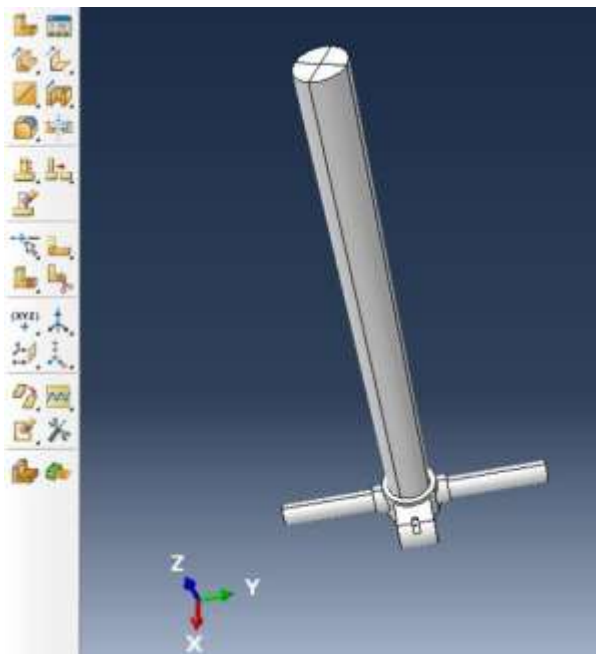
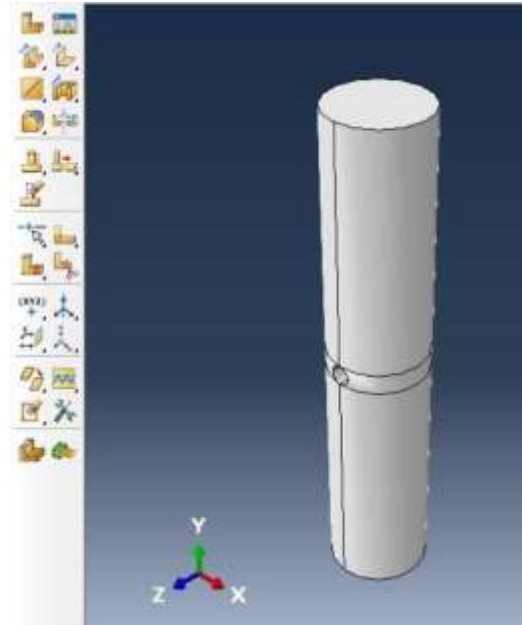
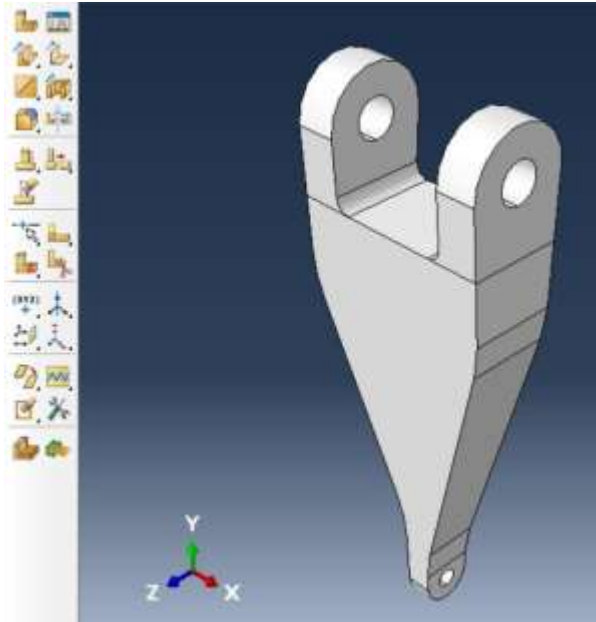
The software uses numerical methods to model and solve complex engineering problems. It supports a range of analysis types, including structural stress, thermal, dynamic, and schematic analysis. Abaqus can simulate interaction between components in a system, enabling users to better understand interdependencies and predict outcomes.

**Applications in mechanical engineering:** Abaqus is commonly used to analyze and simulate mechanical structures, including evaluating the strength and stiffness of

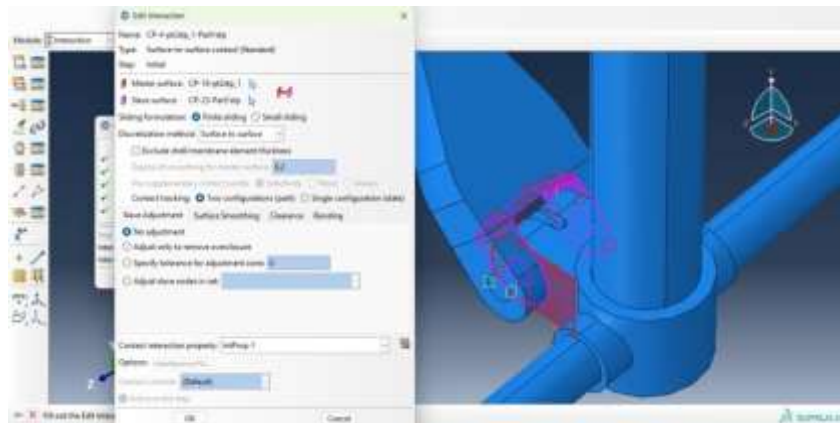
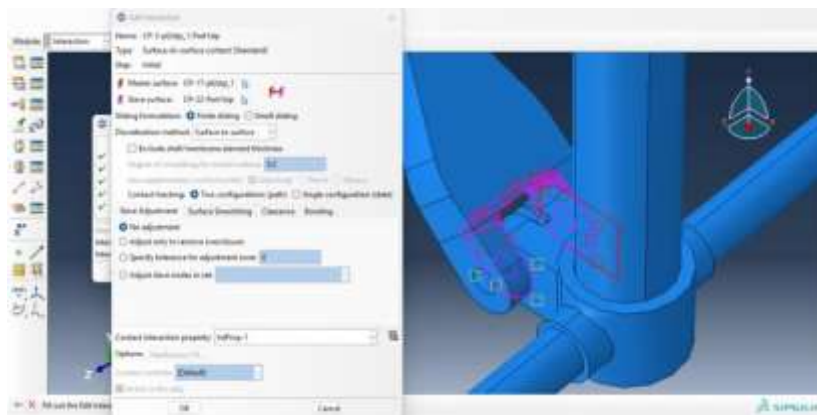
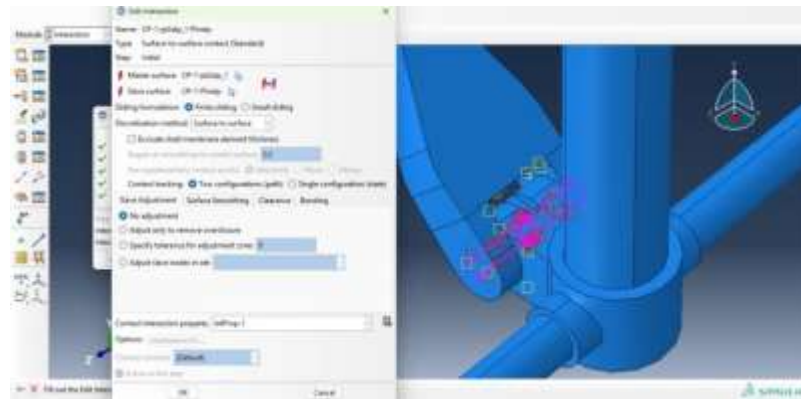
components, machines, and equipment. It also facilitates design optimization and material usage efficiency.

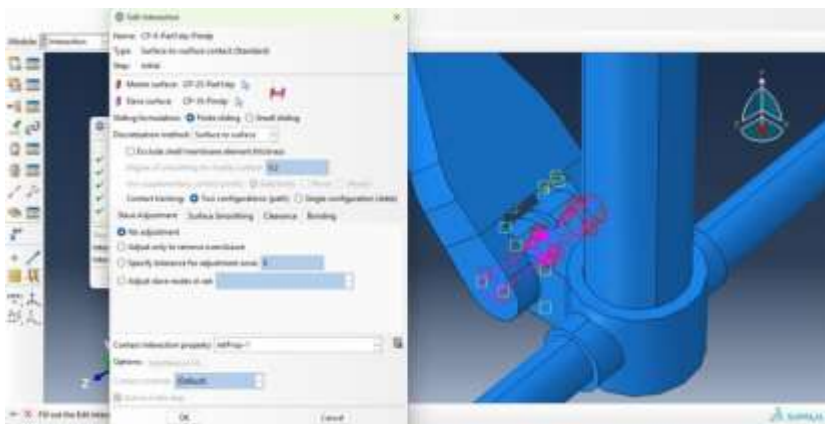
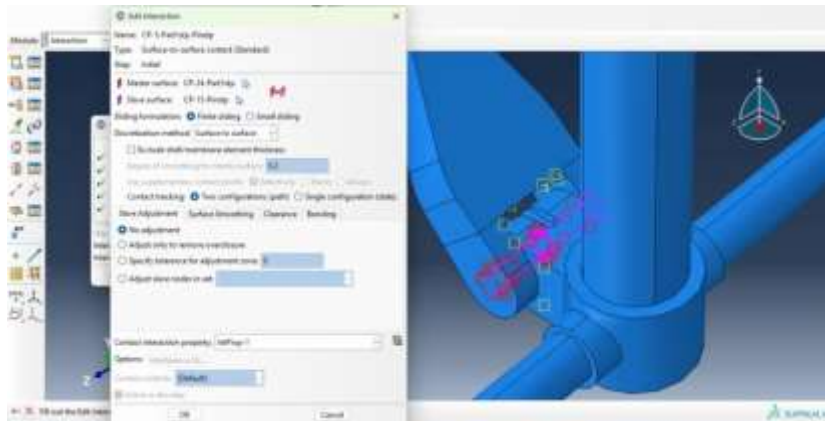
### 5.3.2. Initial settings:

- 3D model configuration

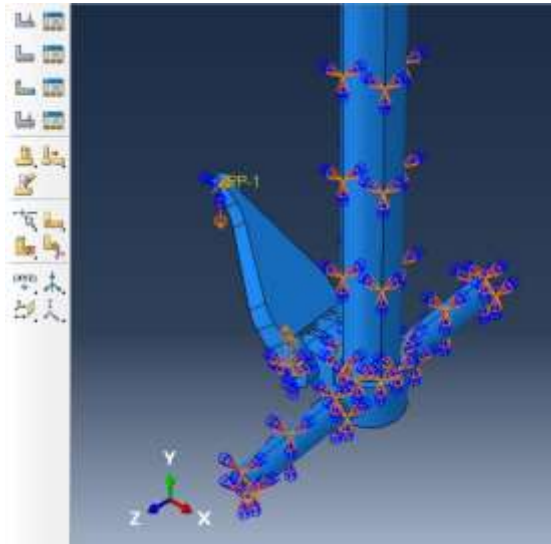


- Contact interactions





- **Boundary conditions:**
  - **Pin:** One end fixed; the other end assigned a displacement boundary condition to simulate parallelism deviation, with displacement increasing from 0 to 1 mm.
  - **Torque Link:** Motion constraints applied to simulate realistic rotational behavior.
  - **Sliding Tube:** Fixed at strategic locations to prevent global motion of the assembly.



#### 5.4. Simulation results analysis:

##### 5.4.1. Stress evaluation across sifferent scenarios:

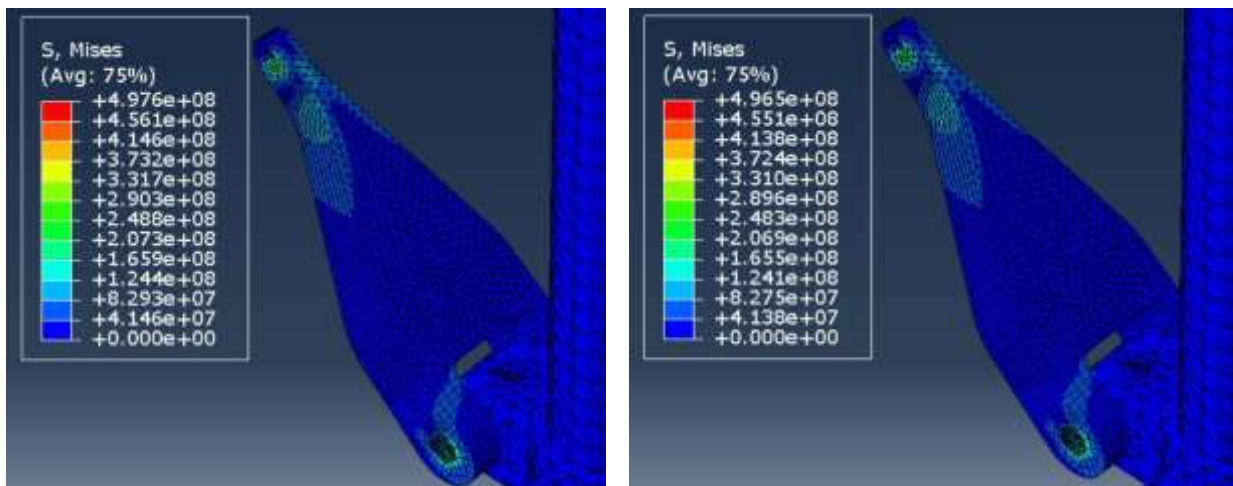


Figure 5.1. Stress Result – Case 1 and Case 2

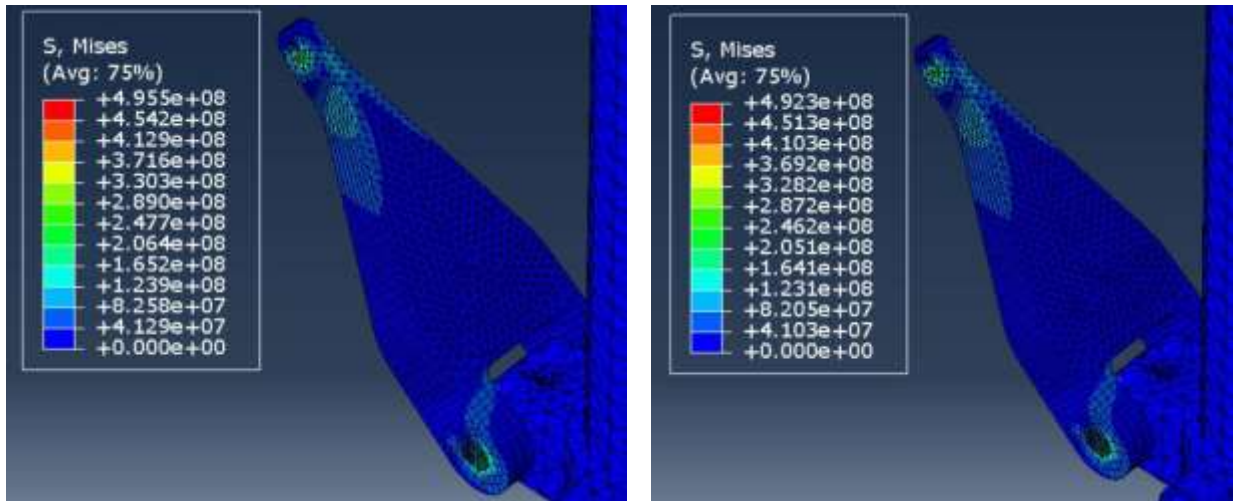


Figure 5.2. Stress Result – Case 3 and Case 4

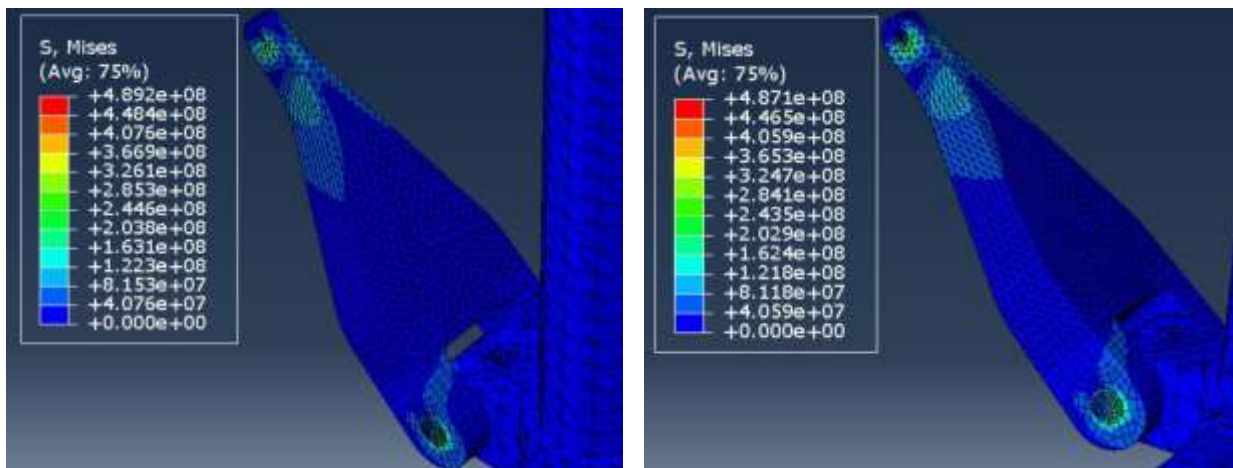


Figure 5.3. Stress Result – Case 5 and Case 6

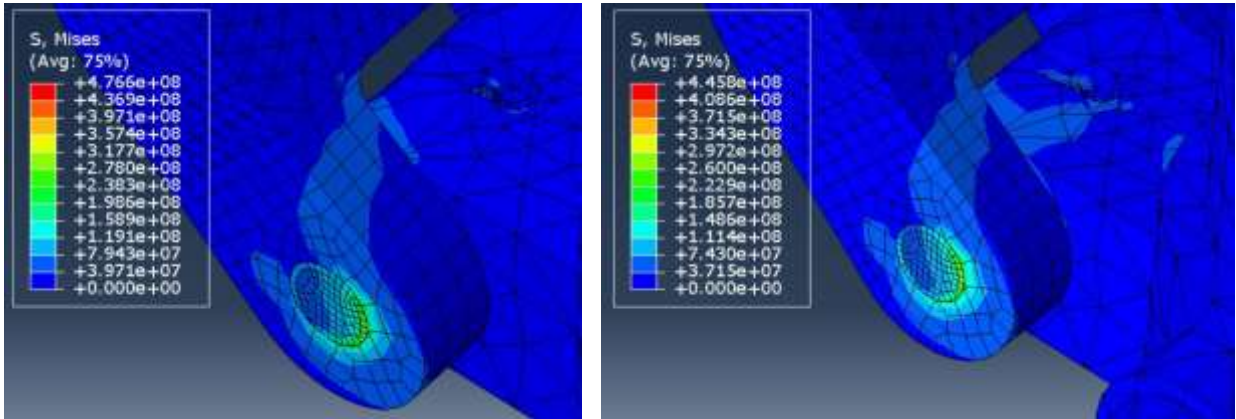


Figure 5.4. Stress Result – Case 7 and Case 8

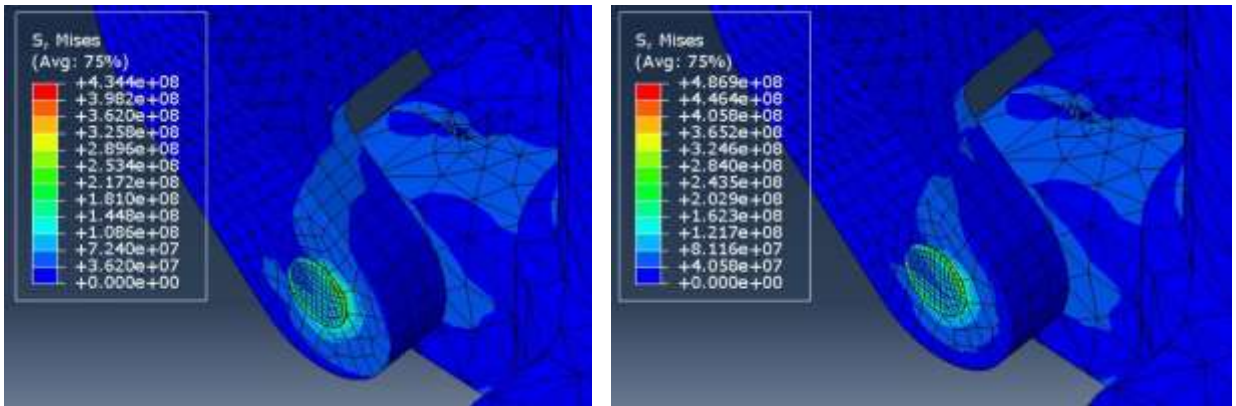


Figure 5.5. Stress Result – Case 9 and Case 10

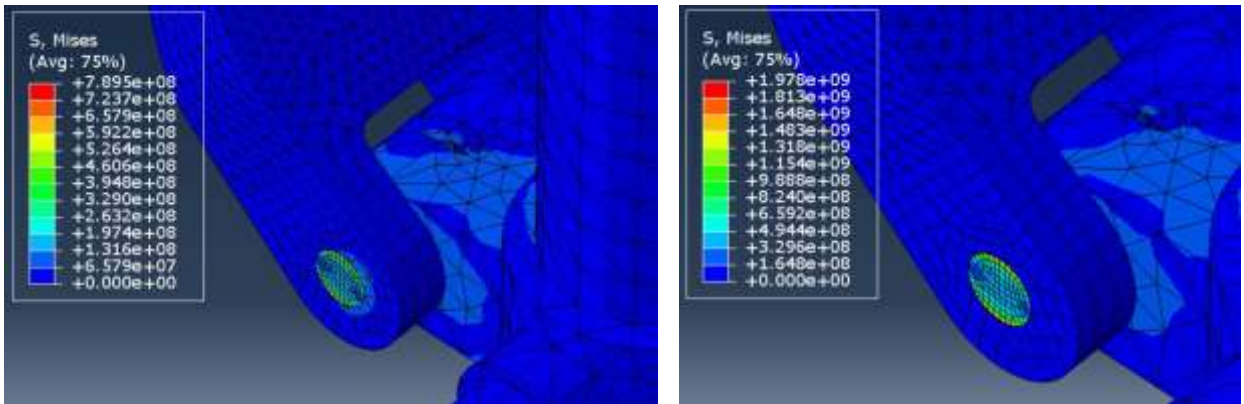


Figure 5.6. Stress Result – Case 11 and Case 12

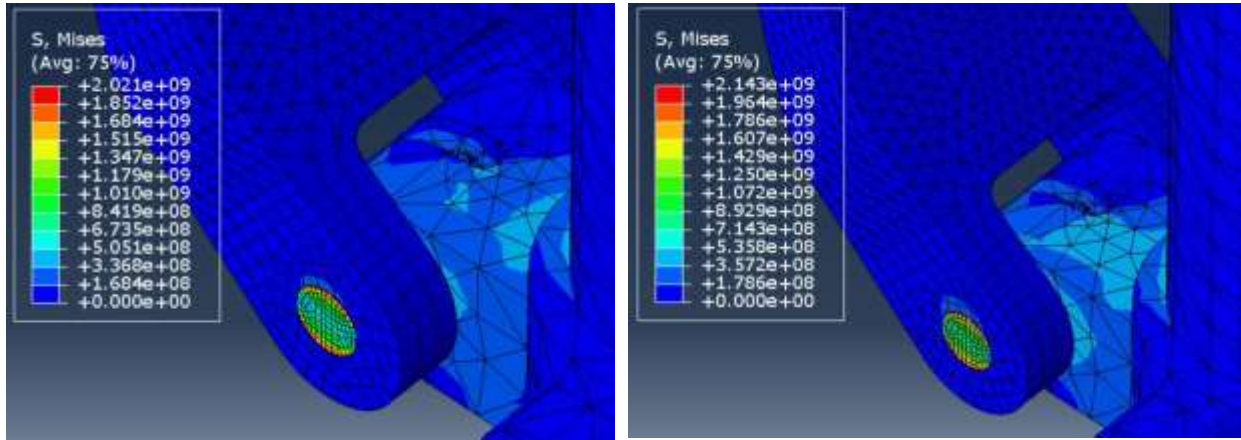
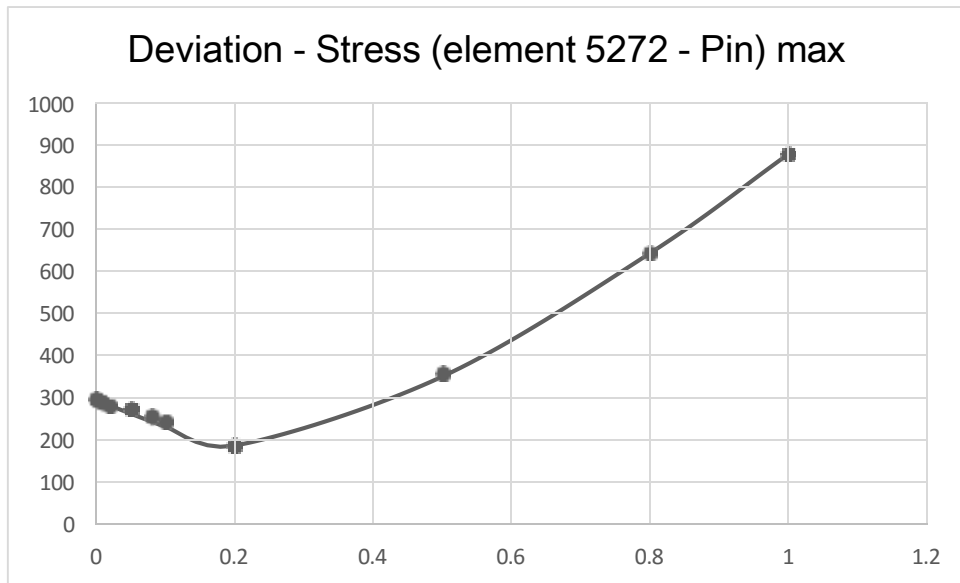
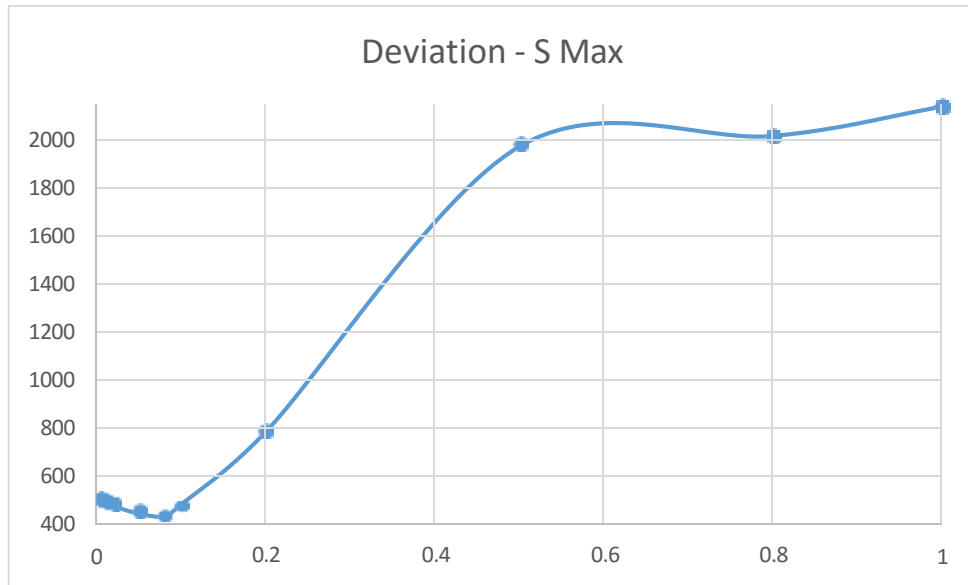


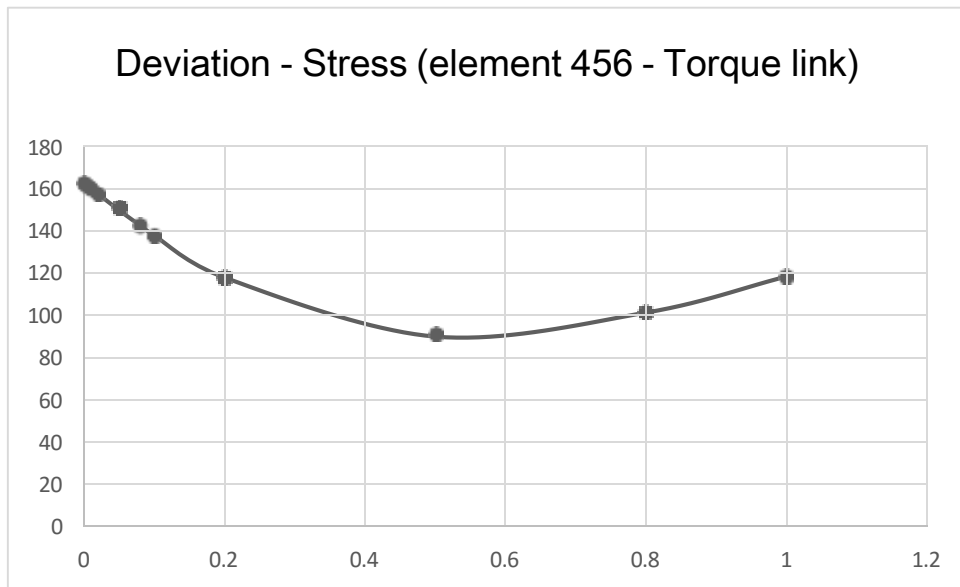
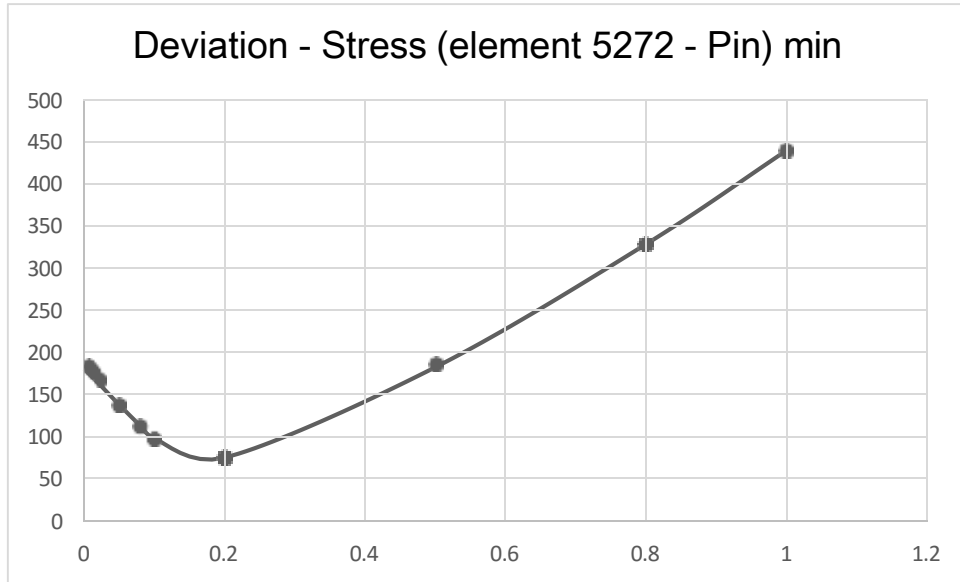
Figure 5.7. Stress Result – Case 13 and Case 14

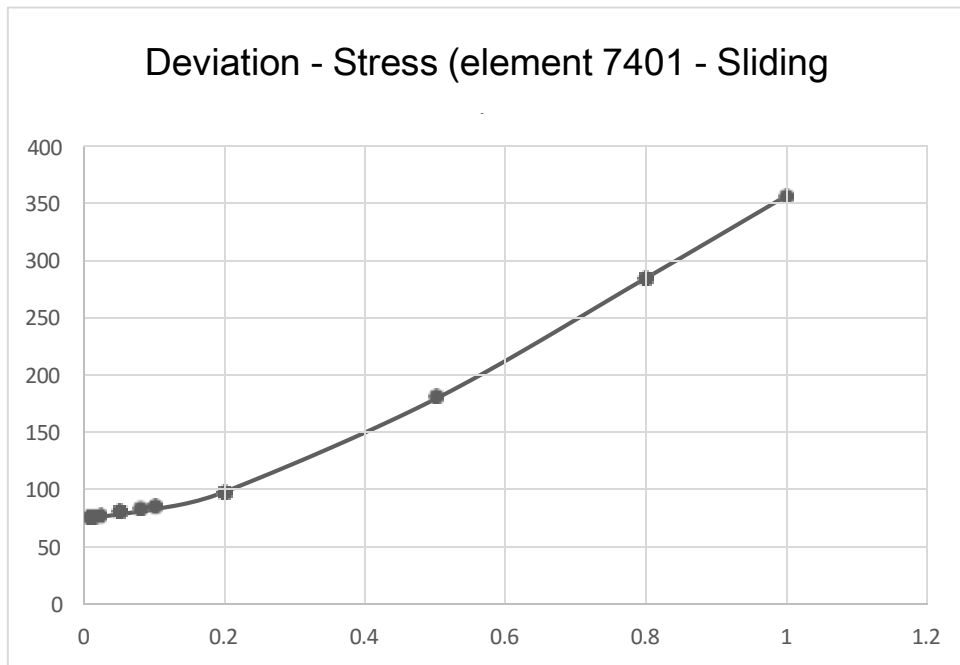
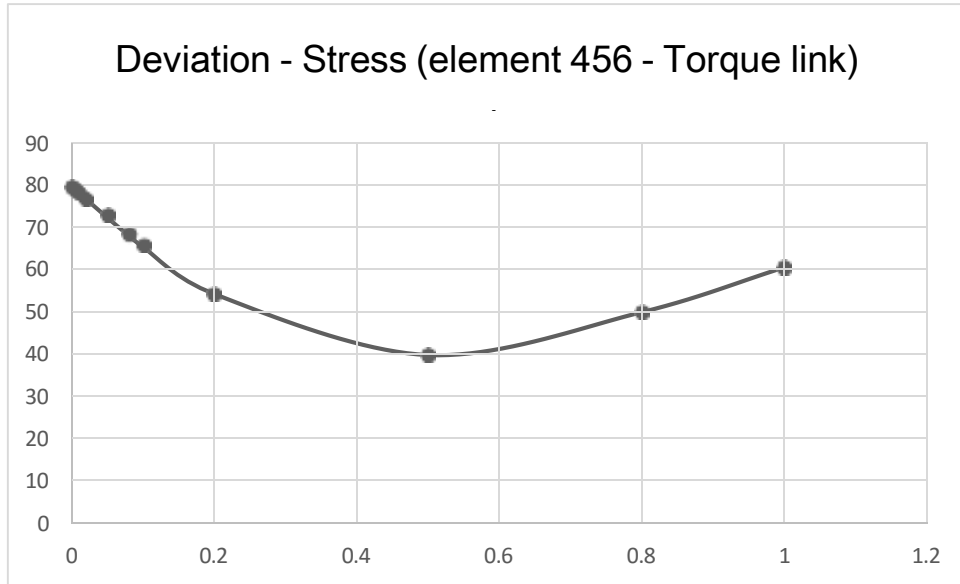
Table 5.1. Stress Distribution under Corresponding Deviations

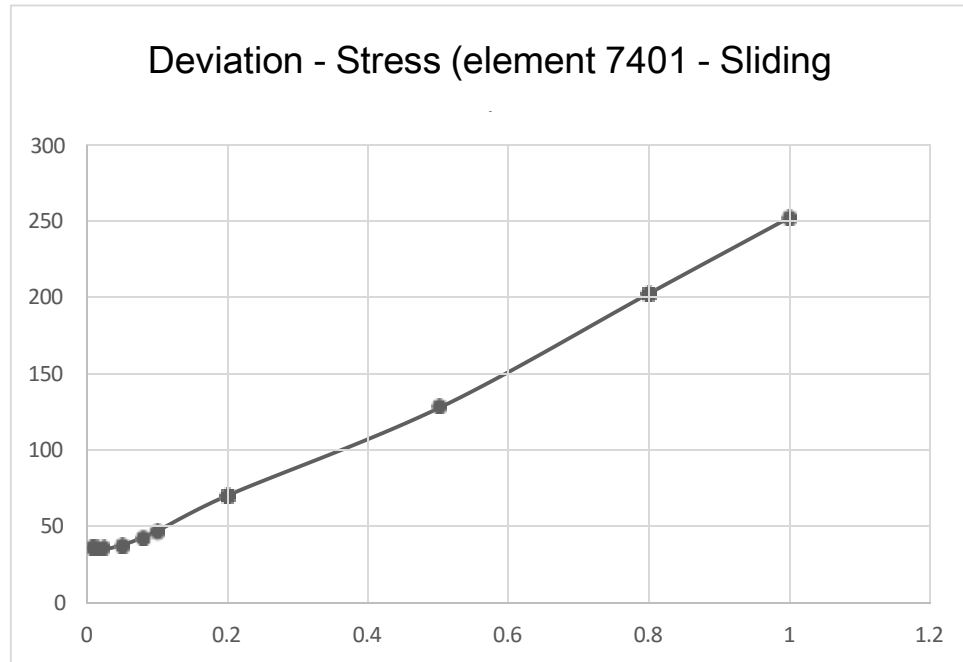
Deviation (mm)	Max (MPa)	Element (5272) max (MPa)	Element (5272) min (MPa)	Element (456) max (MPa)	Element (456) min (MPa)	Element (7401) max (MPa)	Element (7401) min (MPa)
0	497.6	299.821	181.25	163.002	79.688	75.4566	34.6996
0.001	496.5	299.003	180.527	162.735	79.5598	75.5277	34.6707
0.002	495.5	298.185	179.752	162.2468	79.4314	75.5988	34.6449
0.005	492.3	295.677	177.387	161.668	79.0308	75.817	34.596
0.008	489.2	293.107	174.971	160.87	78.5807	76.036	34.5798
0.01	487.1	291.38	173.348	160.34	78.281	76.1811	34.5824
0.02	476.6	283.628	164.994	157.681	76.7814	76.9016	34.8206
0.05	445.8	264.393	139.062	150.024	72.3741	79.2125	37.9115
0.08	434.4	245.55	114.185	142.761	68.1424	81.7882	43.1535
0.1	486.9	233.844	99.2781	138.11	65.4836	83.6201	47.1863
0.2	789.5	188.743	76.381	118.234	54.3705	98.8379	70.4622
0.5	1978	352.636	183.599	90.3484	39.967	179.864	127.477
0.8	2021	645.186	329.521	101.689	50.1007	285.399	202.583
1	2143	880.42	440.639	118.749	60.67	357.174	252.288

- **Graphs Generated from Simulation Results**









- **Observation:**

- As observed in the chart, for elements belonging to the Pin and Torque Link, when the displacement increases to a certain threshold, the stress at both the maximum and minimum stress points tends to increase, rather than decrease as it did previously.
- For elements located near the interaction region with the Pin on the Sliding Tube, the stress tends to increase almost proportionally with the displacement.
- The displacement – maximum stress (Deviation – Max) graph shows noticeable differences across stages because the stress is evaluated over the entire simulated assembly. As a result, the stress – concentrated regions may shift from one position to another or from one component to another.

#### ***5.4.2. Stress distribution analysis with different pin materials:***

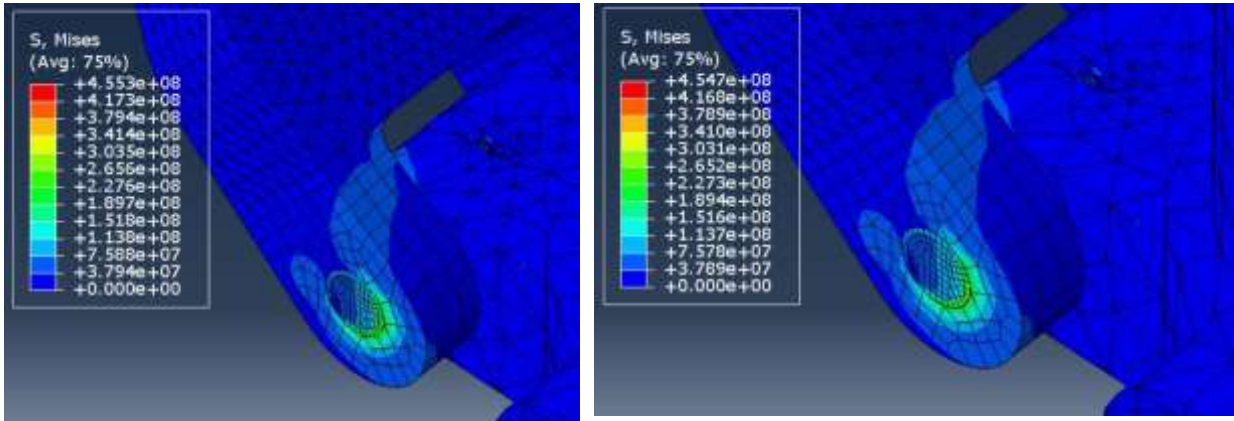


Figure 5.8. Stress Result – Case 1 and Case 2 (different pin material)

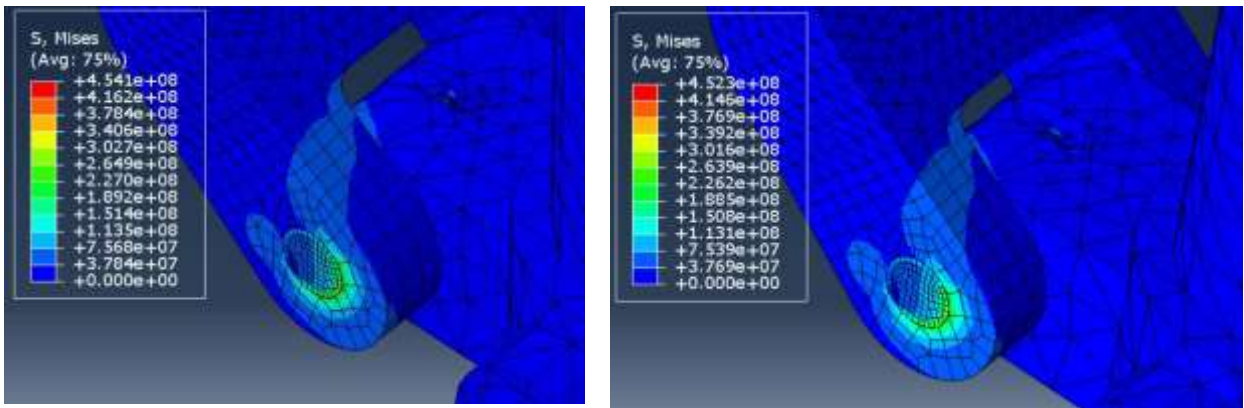


Figure 5.9. Stress Result – Case 3 and Case 4 (different pin material)

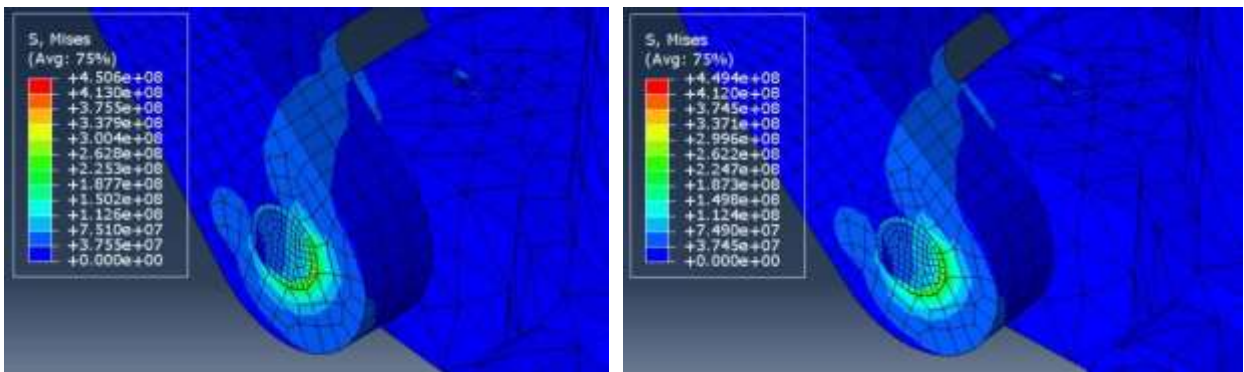


Figure 5.10. Stress Result – Case 5 and Case 6 (different pin material)

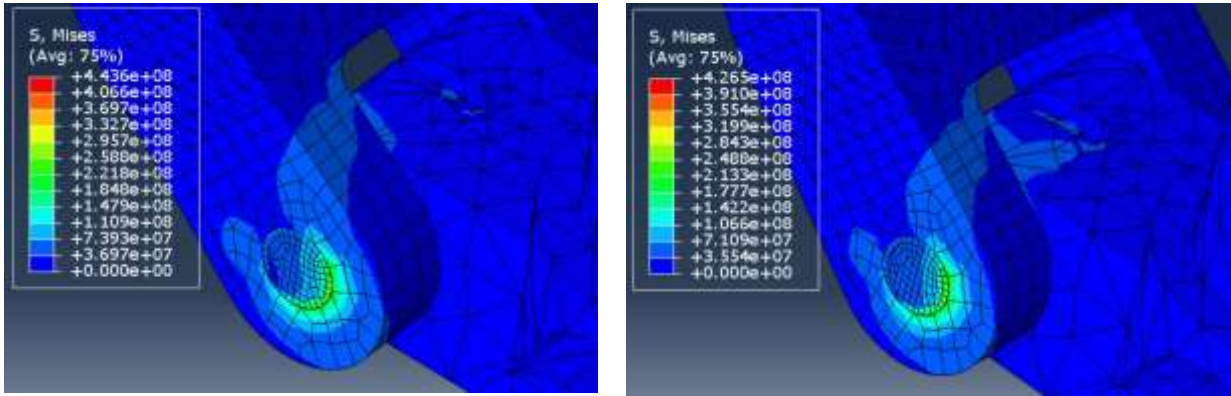


Figure 5.11. Stress Result – Case 7 and Case 8 (different pin material)

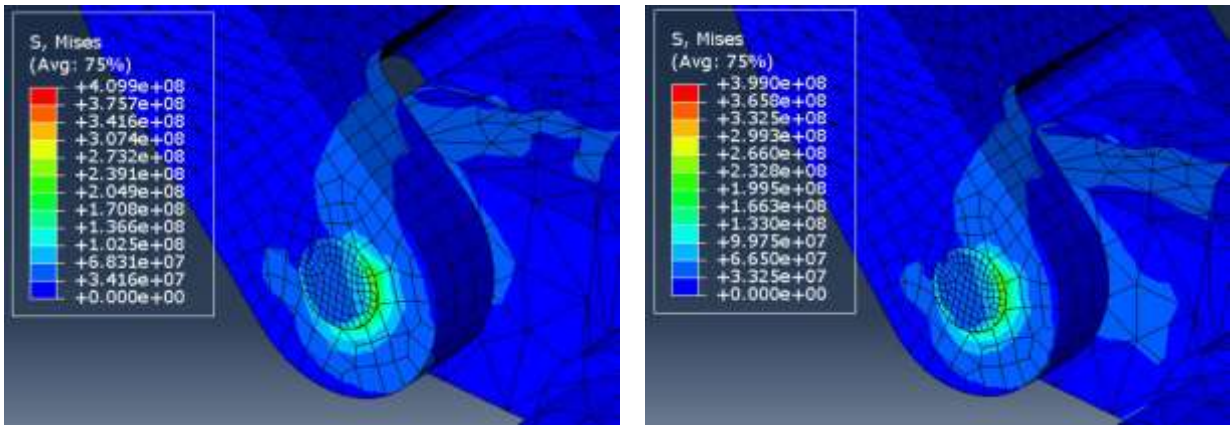


Figure 5.12. Stress Result – Case 9 and Case 10 (different pin material)

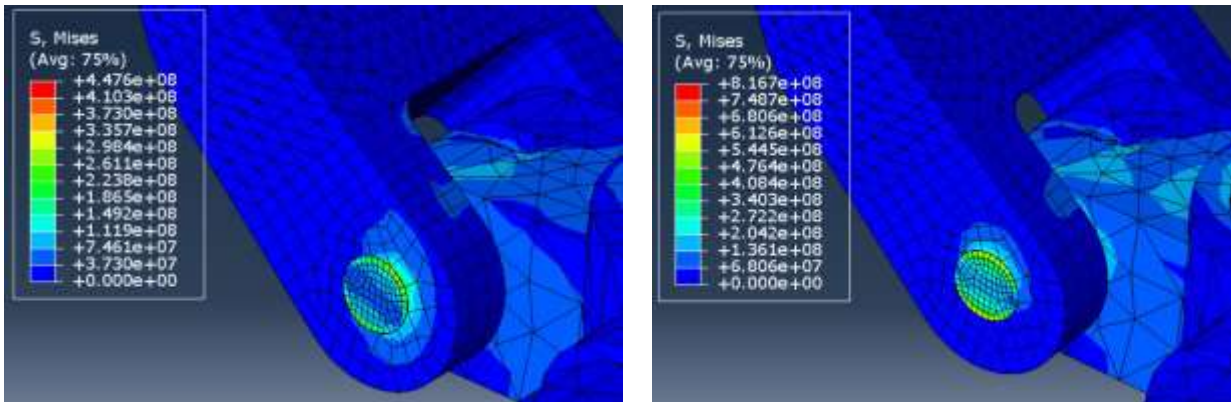


Figure 5.13. Stress Result – Case 11 and Case 12 (different pin material)

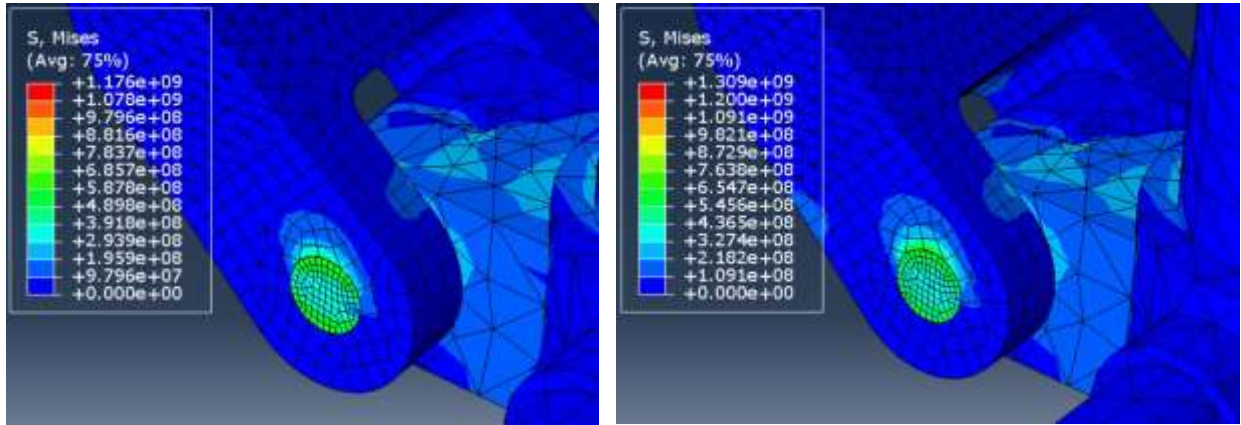
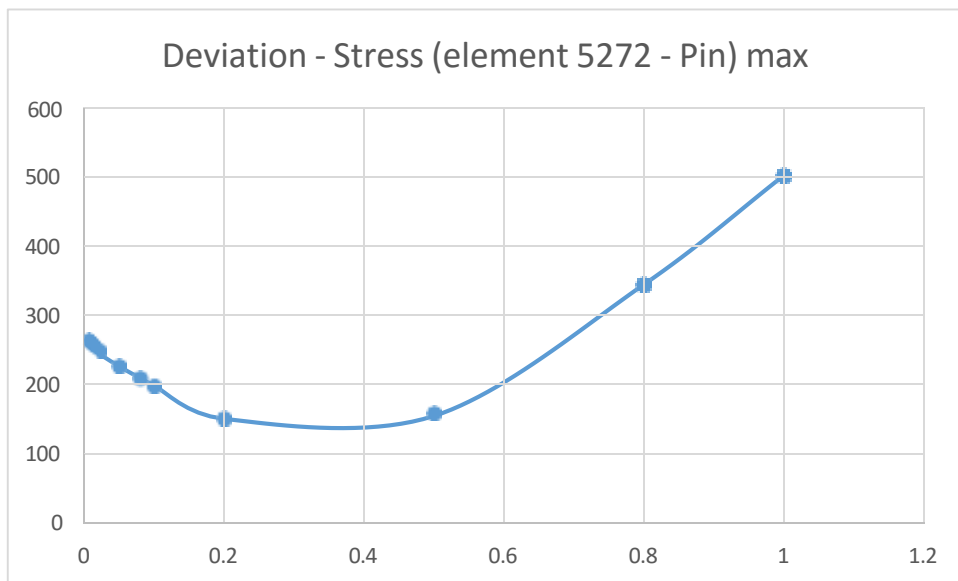
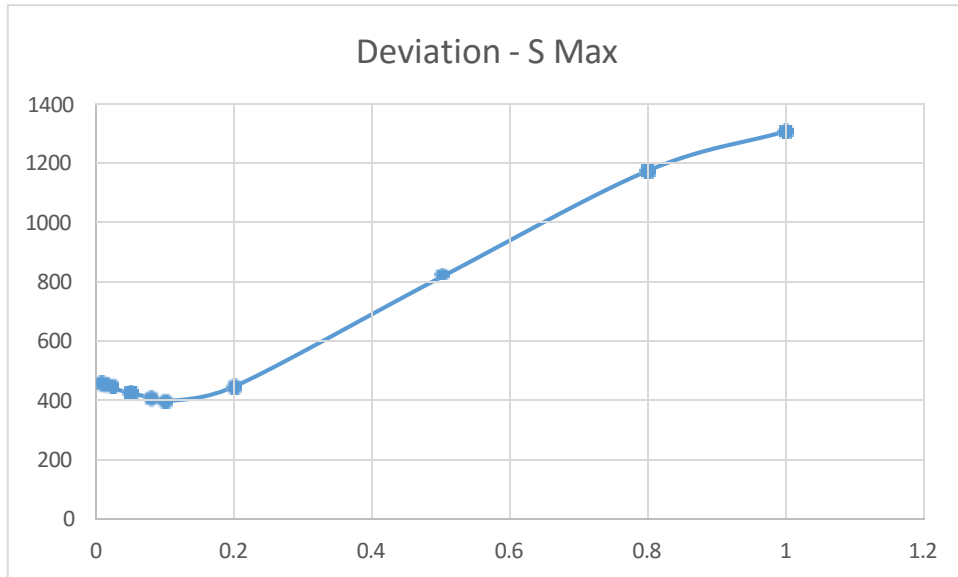


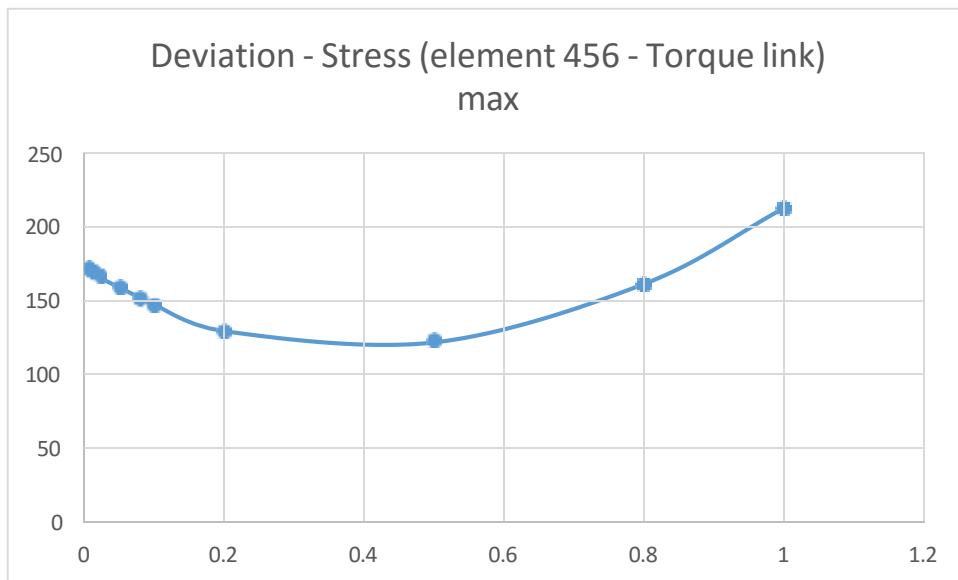
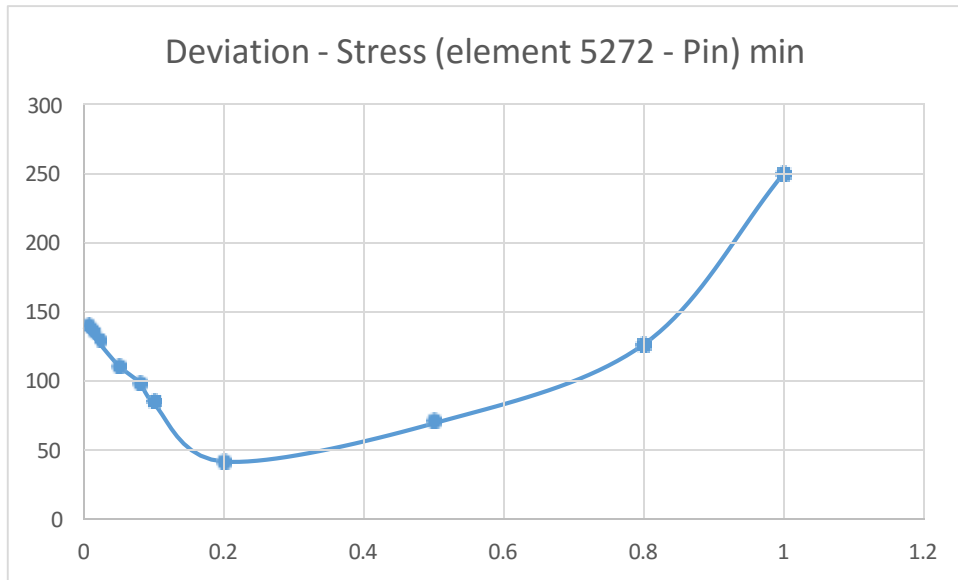
Figure 5.14. Stress Result – Case 13 and Case 14

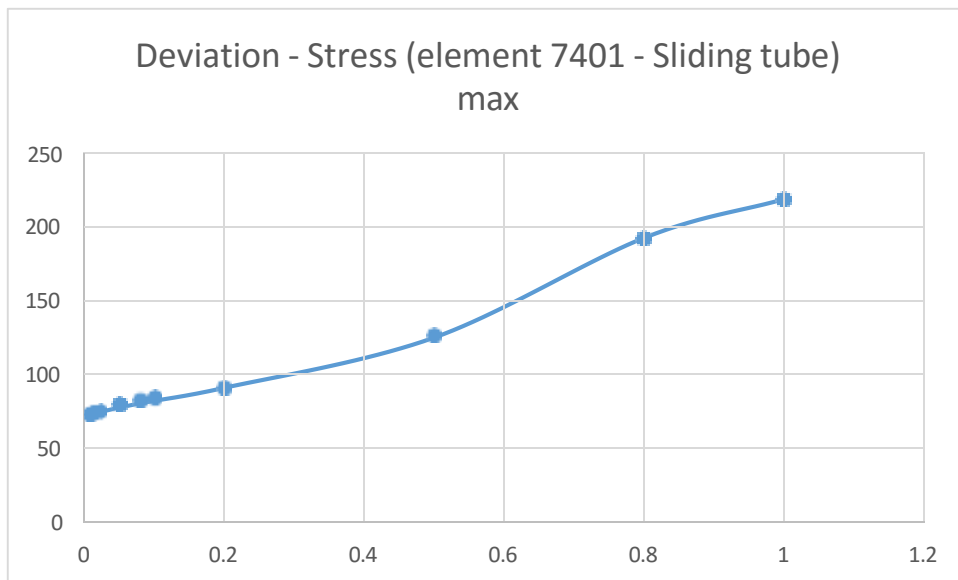
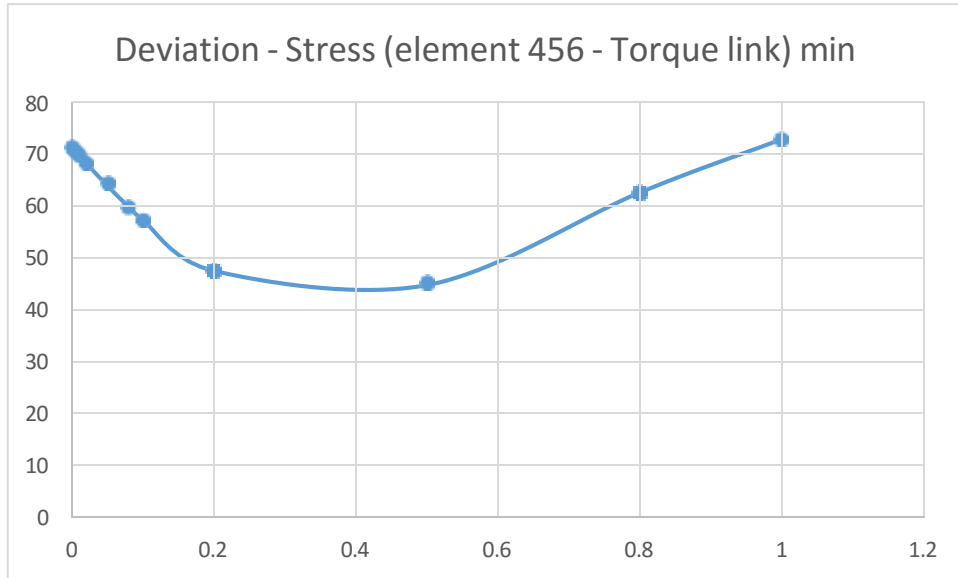
Table 5.2. Stress Distribution under Corresponding Deviations (different pin material)

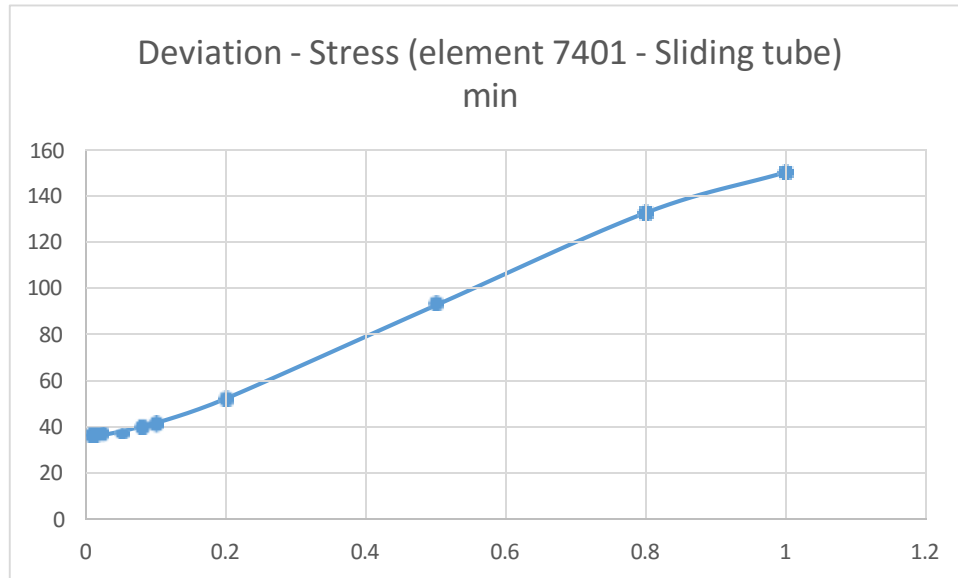
Deviation (mm)	Max (MPa)	Element (5272) max (MPa)	Element (5272) min (MPa)	Element (456) max (MPa)	Element (456) min (MPa)	Element (7401) max (MPa)	Element (7401) min (MPa)
0	455.3	262.172	139.906	171.634	71.4779	72.7421	35.7226
0.001	454.7	261.402	139.41	171.37	71.3213	72.8448	35.7451
0.002	454.1	260.632	138.913	171.108	71.1651	72.9485	35.7697
0.005	452.3	258.322	137.428	170.327	70.6998	73.2607	35.852
0.008	450.6	256.005	135.941	169.549	70.2368	73.5773	35.9469
0.01	449.4	254.462	134.944	169.035	69.9301	73.791	36.0208
0.02	443.6	246.769	128.989	166.522	68.4121	74.867	36.4793
0.05	426.5	227.616	111.488	159.356	64.0626	78.053	38.2418
0.08	409.9	210.685	99.1949	152.327	59.9719	81.0068	40.4522
0.1	399	199.858	84.013	147.705	57.4522	82.656	41.8796
0.2	447.6	151.877	42.4813	129.734	47.6608	91.411	52.4736
0.5	816.7	155.868	70.1148	122.052	44.9024	125.357	92.8292
0.8	1176	345.582	127.042	161.537	62.7493	192.719	132.857
1	1309	503	250.401	212.9	73.0242	218.925	150.372

- **Graphs Generated from Simulation Results**









- **Observation:**

- Similarly, for elements associated with the Pin and Torque Link, when the displacement increases to a specific value, both the maximum and minimum stress points tend to rise, rather than continue decreasing as observed in earlier stages.
- For elements located near the interaction region with the Pin on the Sliding Tube, the stress shows an almost linear increase corresponding to the displacement.
- The displacement – maximum stress (Deviation – Max) curve displays variation across different phases, as the stress is evaluated across the entire simulated assembly. Consequently, stress concentration zones may shift from one position to another, or from one component to another.
- The shift in trend occurs more slowly compared to the case without a material change in the Pin. This suggests that the material used in this scenario plays a significant role in delaying the onset of stress reduction as displacement increases.

## Chapter 6

### CONCLUSIONS AND RECOMMENDATIONS

#### **6.1. General conclusion:**

This graduation project, titled “*Design of assembly process and evaluation of GD&T influence on accuracy and stress of nose landing gear*” has successfully fulfilled its initial research objectives, achieving both theoretical depth and practical relevance. Specifically, the project addressed a dual challenge: (1) standardizing the assembly process for a precision mechanical subassembly, and (2) quantitatively assessing the effects of geometric deviations (GD&T) on stress states using numerical simulation tools.

The methodology followed a closed-loop engineering approach, starting from theoretical research, defining technical requirements, building an assembly model, and finally validating assumptions through simulation. The use of Abaqus as a simulation tool demonstrated that even minor geometric deviations—within manufacturing tolerances—can have a pronounced impact on stress distribution, thereby affecting the structural integrity and operational lifespan of the assembly.

#### **6.2. Key results achieved:**

##### ***6.2.1. Assembly process and GD&T application:***

- **Development of a structured assembly process for the torque link subassembly:** Based on actual aircraft maintenance documentation (A320 nose gear), the project constructed a clear, visual, and step-by-step assembly procedure. Exploded views and detailed annotations were used to clarify the role of each component (e.g., lock plates, pins, lugs), meeting the requirements of a real-world technical manual.
- **Systematic application of GD&T theory:** Fundamental knowledge on Geometric Dimensioning and Tolerancing, particularly parallelism and concentricity, was studied and directly applied to define boundary conditions and input parameters for simulation. This demonstrated the seamless integration between mechanical design standards and virtual analysis.

### **6.2.2. Finite element analysis (FEA):**

- **Development of a reliable and efficient simulation model:** A 3D finite element model of the pin – hole assembly was successfully created in Abaqus, simulating contact conditions, boundary constraints, and applied loads. The method of using prescribed displacement to emulate angular misalignment proved effective in representing realistic GD&T deviations.
- **Quantitative insights into non-linear effects of parallelism deviation:**
  - Non-uniform stress response: Stress distribution varied significantly between different zones. For instance, stresses at the hole edge of the torque link first decreased slightly and then rose sharply, while stresses at the piston lug increased almost linearly. This emphasized the need for multi-point evaluation rather than single-point analysis.
  - Material sensitivity: The simulations showed that material selection for the pin (e.g., A7075 – T6 vs. 300M steel) significantly influences the stress response and deviation thresholds. Materials with better local plastic deformation capability help redistribute stress more effectively.
  - Critical impact of small deviations: Even deviations within drawing tolerance limits can lead to notable stress concentration at edges and contact zones, posing fatigue initiation risks and reducing service life.

### **6.3. Limitations:**

Despite its achievements, the project acknowledges the following limitations:

- **Model scope:** The simulation was limited to a single subassembly (torque link) and did not consider interactions with other components of the nose landing gear system.
- **Static loading conditions only:** The analysis considered static loads and did not reflect dynamic or impact loads experienced during landing and taxiing.
- **Single-parameter GD&T analysis:** The study focused solely on parallelism deviation without conducting a comprehensive **tolerance stack-up** analysis involving multiple deviation types.
- **Lack of experimental validation:** Due to equipment and resource limitations, the simulation results have not been cross-verified with experimental data, which is essential for full validation.

## **6.4. Recommendations and future work:**

### **6.4.1. Engineering recommendations:**

- **Design and control of critical GD&T features:** Engineers should define and strictly control essential geometric tolerances such as parallelism and concentricity at load-bearing pin-hole joints. These should be mandatory, not optional, requirements.
- **Material selection with assembly tolerance in mind:** Beyond strength, materials should be evaluated based on their ability to tolerate assembly misalignments. Preference should be given to materials with good local plasticity to better manage stress concentrations.
- **Enhanced assembly and quality control procedures:** Assembly workflows should incorporate alignment checks using specialized gauges to ensure GD&T compliance not only during manufacturing but also during final assembly stages.

### **6.4.2. Technical development directions:**

- **Dynamic simulation modeling:** Future work should include dynamic loading conditions (e.g., Abaqus/Explicit) to analyze impact behavior during landing. Incorporating factors such as contact friction and clearance will improve simulation realism.
- **Fatigue analysis:** Based on obtained stress distributions, fatigue life analysis can help predict the long-term effects of GD&T deviations on the durability of the assembly.
- **Comprehensive tolerance stack – up analysis:** Applying 1D, 2D, or 3D tolerance stack-up techniques will allow evaluation of the combined effects of multiple geometric deviations on assembly performance.
- **System – level integration and validation:** Long-term research may involve developing a full nose gear model, integrating mechanical, hydraulic, and control systems. 3D scanning can be used to digitize real components, enabling direct comparison between measured and simulated results for model validation and calibration.

## **6.5. Proposed solutions for process control:**

To further improve process control and effectiveness in real-world aerospace manufacturing, the following advanced measures are recommended:

- **Implement tolerance stack – up simulation:** Utilize software such as CATIA Tolerancing or 3DCS to predict accumulated dimensional variations during assembly. This minimizes fitting issues and ensures part interchangeability on the production floor.
- **Adopt digital twin technology:** Integrate 3D assembly models into a digital twin platform for virtual monitoring of assembly performance, enabling process optimization before physical implementation.
- **Develop a standard operating procedure (SOP):** Create SOPs with illustrated steps and QR-code component tracking to streamline quality control, minimize human error, and assist technician training.
- **Enhance GD&T training with MBD (Model – Based Definition):** Leverage 3D annotated models to embed inspection dimensions directly into CAD files, replacing reliance on traditional 2D drawings and improving inspection efficiency.
- **Introduce automation to torque link assembly:** Consider semi-automated tools or AR-assisted assembly techniques to improve repeatability and reduce operator dependency, especially for tasks like spline alignment or safety wiring.
- **Evaluate maintenance and lifecycle factors in design:** Integrate maintainability into early design stages by using quick-release features, corrosion-resistant coatings, and standardized fasteners to facilitate inspection, repair, and disassembly.

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